VSB TECHNICAL UNIVERSITY OF OSTRAVA | FACULTY OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

Short circuit calculation according GOST standard

Výpočet zkratů dle normy GOST

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Diploma Thesis

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-Basic theory and terminology related to the short-circuit calculations according to the GOST standard.
-Models of the power system elements (generators, transformers, cables, overhead lines, asynchronous motors etc.) for GOST short-circuit calculations.
-Proper software selection and detail description of the GOST short-circuit calculation procedure of it.
-Application of the GOST short-circuit calculations on the chosen industrial network.

References:

-GOST R 52735-2007. Short-circuits in electrical installations. Calculation methods in alternating current electrical installations with voltage above 1 kV, 2008
-Leading directions for relay protection. Short circuit current calculations for relay protection and system automatics in power network 110 – 750 kV, Energiya, Moscow, 1979
-IEC 60909. Short-circuit currents in three-phase a.c. systems, 2016
-RastrKZ user's manual, third edition, 2019

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Abstract and keywords

Abstraktní

Správný výpočet zkratových proudů je velmi důležitým úkolem z hlediska návrhu elektrické instalace, protože ovlivňuje dimenzování zařízení a nastavení ochran zařízení. Existuje několik způsobů, jak vypočítat zkratový proud. Tato diplomová práce ukazuje přístup standardu GOST, který je široce rozšířen na území– Ruské federace a bývalých republik Sovětského svazu.

Existují dva standardy GOST, které řídí výpočet zkratového proudu v sítích se jmenovitým napětím pod a nad 1 kV - GOST 28249-93 a GOST R 52735-2007. Bohužel tyto standardy mají nejasnou strukturu a někdy postrádají informace. Hlavním cílem této diplomové práce je získat doporučení výše uvedených standardů, přidat některé chybějící informace z doplňkové dokumentace a sloučit je do jednoho transparentního dokumentu, který může pomoci osobě neznalé GOST standardů samostatně a spolehlivě vypočítat zkratové proudy podle normy GOST.

Klíčová slova

Proud, porucha, zkrat, GOST, špičkový proud, RastrKZ, výpočet zkratového proudu, aperiodická složka.

Abstract

Correct calculation of the short-circuit currents is a very important task in terms of designing an electrical installation because it affects the sizing of the equipment and setting of the protection relays. There are different ways how to calculate the short-circuit current. This diploma thesis shows the approach of the GOST standard which is widely spread in the territory of the Russian Federation and former Soviet republics.

There are two GOST standards that govern the calculation of the short-circuit current in the networks with rated voltage below and above 1 kV – GOST 28249-93 and GOST R 52735-2007, respectively. Unfortunately, these standards have unclear structure and sometimes lack information, so the main purpose of this diploma thesis is to get recommendations of mentioned above standards, add some missing information from the supplementary documentation and merge them into one transparent document which can help an unfamiliar person to calculate short-circuit currents in accordance with GOST standard independently and confidently.

Keywords

Current, fault, short-circuit, GOST, peak current, RastrKZ, short-circuit current calculation, aperiodic component.

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Introduction

GOST is a system of standardization which is commonly used in the territory of the Commonwealth of Independent States (CIS), it means that particularly short-circuit current calculations in the field of electrical power networks in the CIS should be performed according to GOST standard. Use of the GOST standard is not so widely spread in the territory of the European Union, but still, there are some companies which have interests in the territory of the CIS and meet requirements to use GOST standard instead of IEC one. Therefore, it is necessary to sort out in details what stands behind of calculations according to GOST and moreover compare the two mentioned above standards in terms of a difference in results and their reliability.

Chapter 1 defines the basic terminology used in GOST standards and describes the purposes for calculation of the short-circuit currents and their components.

Chapter 2 sets the models of typical power system elements and approach to calculate their parameters in different units, also show the basic rules to make up an equivalent circuit for the purpose of short-circuit current calculation.

Chapter 3 shows the general idea of how to calculate symmetrical or unsymmetrical short-circuit currents and their components, gives specificities of calculation in the networks with rated voltage below and above 1 kV.

Chapter 4 describes the choice of the software product called RastrKZ, which was used in the practical part of this diploma and its functionality and specificities.

Chapter 5 consists of the practical calculation of the short-circuit currents in the real industrial network according to the GOST standard using the RastrKZ software.

Chapter 6 contains the comparison of results calculation according to the GOST and IEC standards, explains the reasons of the difference in results and their consequences.

1. Basic theory and terminology related to the short-circuit calculations according to the GOST standard

At first, the basic terminology used in GOSTs [1],[2] should be described. Some common terms are in the list down below.

Short-circuit – any accidental or intentional connection between different points (phases) of the electrical installation which is not a proper mode of operation and creates the currents in the branches of the electrical installation exceeding the currents of the steady-state mode.

Phase-to-earth fault – short-circuit in the electrical network with grounded or effective-grounded neutral caused by the accidental or intentional connection of the phase conductor with the earth.

Phase-to-phase fault – short-circuit connection between two phases in the three-phase electrical power system.

Phase-to-phase-to-earth fault – short-circuit in the electrical network with grounded or effective-grounded neutral caused by the accidental or intentional connection of two phase's conductors and earth.

Three-phase fault – short-circuit connection between three phases in the three-phase electrical power system.

Symmetrical short-circuit – short-circuit when all three phases are in the same operating conditions.

Unsymmetrical short-circuit – short-circuit when one phase has different operating conditions than the other two.

Distant short-circuit – such a short-circuit where the amplitude of the periodic component of the short-circuit current at the beginning of the fault is approximately the same as the one at any arbitrary moment of time.

Close short-circuit – such a short-circuit where the amplitude of the periodic component of the current at the beginning of the fault drastically differs from the one at any arbitrary moment of time.

Aperiodic component of the short-circuit current – a component of the short-circuit current which is not periodic and usually has an exponential character.

Symmetrical component of the short-circuit current – a component of the short-circuit current which has a periodic character.

Peak short-circuit current – maximum possible instantaneous value of the short-circuit current.

Initial symmetrical short-circuit current – r.m.s. value of the symmetrical component of the short-circuit current at the moment when short-circuit occurred.

As the basic terms are described, it should be mentioned why we need to calculate short-circuit current. Basically, values of short-circuit currents are used for choosing and verification of electrical equipment ratings and defining proper settings of relay protection and protective device coordination.

For means of choosing electrical equipment ratings usually, we have to know:

1) Initial symmetrical short-circuit current;

2) Initial aperiodic component of the short-circuit current;

3) Peak short-circuit current.

For means of defining the settings of relay protection and protective device coordination, we have to know the maximum and minimum values of symmetrical short-circuit current at the instant of the short-circuit fault and in any arbitrary time after short-circuit occurred.

2. Models of the power system elements for the short-circuit calculations according to the GOST standard

2.1 Basic rules to make up the equivalent circuit

Calculation of the short-circuit current usually starts with the equivalent circuit of the network. This circuit consists of all elements in the network which carry short-circuit current. These elements should be represented by their models.

In case of symmetrical fault, it's enough to have only one circuit consisting of models which are represented by positive sequence reactance and resistance. Rotating machines and complex load e.g. asynchronous motors, synchronous motors and generators should be presented by a subtransient impedance and electromotive force. Transformers, autotransformers and reactors should be represented by their models.

Short-circuit current calculation in case of unsymmetrical faults is performed using the method of symmetrical components. To use this method we should in advance make up three equivalent circuits for positive, negative and zero sequences.

The positive sequence circuit remains the same as in case of the symmetrical fault.

The negative sequence circuit is similar to the positive one, but the electromotive forces of rotating machines and complex load should be assumed to be zero. Negative sequence impedance of the synchronous machines should be taken from its datasheet, one of the asynchronous machines can be taken as a subtransient reactance, one of the complex load should be taken using charts from figure 2.9. Negative sequence impedances of transformers, autotransformers, reactors, power lines and cables should be taken as positive ones.

To make up the zero sequence circuit, first of all, the path of the zero sequence current should be defined. To define the path of the zero-sequence current correctly, rules were taken from [3] can be helpful:

1) If the winding of any transformer from the side of the fault is in the delta or wye connection without grounding, a zero-sequence impedance between the primary and secondary winding of such transformers is equal to infinity and we assume that the zero-sequence current is not flowing through that transformer, figure 2.1. Any equipment which is connected to that side of the transformer where is no fault, shouldn't be included in the zero-sequence circuit.

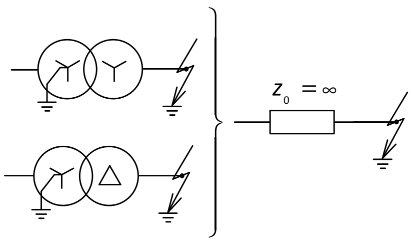


Fig.2.1 – Illustration of the first rule

2) If the windings of any transformer are connected in wye-0/delta, and the winding with wye-0 connection is on the fault's side, then the entire branch from the point of fault to the transformer should be included in the zero sequence circuit, figure 2.2.

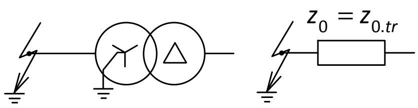


Fig.2.2 – Illustration of the second rule

3) If several power lines are laid in one route, the mutual inductance should be taken into account in the zero sequence circuit. Therefore, GOST states special formulas to calculate zero sequence reactance for power lines where mutual inductance is very important. These formulas can be found in clause 2.3.5 of this chapter.

2.2 Using absolute or relative units and factual or rough transformation methods

2.2.1 Using absolute units with transformation according to factual transformer ratios

If we want to represent elements of the network using absolute units and transform them to some basic voltage level (usually a fault's place voltage level) using factual transformer ratios, these formulas can be used:

$$\begin{gathered}\overset{\circ}{E} = E \cdot n_1 \cdot n_2 \ldots n_m \\ \overset{\circ}{\underline{Z}} = \underline{Z} \cdot n_1^2 \cdot n_2^2 \ldots n_m^2\end{gathered}, \tag{2.1}$$

Where,

E and $\underline{Z}$ – true values of the electromotive force and the complex impedance of any element in the equivalent circuit in absolute units;

$\overset{\circ}{E}$ and $\overset{\circ}{\underline{Z}}$ – transformed values of the electromotive force and the complex impedance of any element in the equivalent circuit;

$n_1, n_2 \ldots n_m$ – ratios of cascade-connected transformers located between the basic voltage step (usually the fault's place voltage level) and a voltage step of an element which parameters are being transformed;

Here and after n_m means the ratio between voltage level on the side of the fault to the voltage level on the other side of the transformer.

If the electromotive force and the complex impedance of the element are given in relative units according to the rated conditions (i.e. these values were calculated using the rated voltage and the rated apparent power), then their values can be represented in absolute units and be transformed to some basic voltage level using factual transformer ratios by means of the formulas below:

$$\begin{gathered}\overset{\circ}{E} = E_{*(rated)} \cdot U_{rated} \cdot n_1 \cdot n_2 \ldots n_m \\ \overset{\circ}{\underline{Z}} = \underline{Z}_{*(rated)} \cdot \frac{U_{rated}^2}{S_{rated}} \cdot n_1^2 \cdot n_2^2 \ldots n_m^2\end{gathered}, \tag{2.2}$$

Where, $\underset{*(rated)}{E}$ and $\underset{*(rated)}{\underline{Z}}$ – the electromotive force and the complex impedance of the element in relative units regarding the rated conditions.

2.2.2 Using relative units with transformation according to factual transformer ratios

If we want to represent elements of the network using relative units and transform them into some basic conditions using factual transformer ratios, this approach should be used:

1) We should pick a basic apparent power S_b and a basic voltage step (usually it's a voltage level of the fault place) – $U_{b.fault}$;

2) Define other voltage steps in relative units using a formula:

$$U_{b.N} = \frac{1}{n_1 \cdot n_2 ... n_m} U_{b.fault}, \tag{2.3}$$

Where,

$n_1, n_2 ... n_m$ – ratios of cascade-connected transformers located between the place of the fault and N – voltage step;

3) Define electromotive forces and complex impedances of all elements in the network in relative units using basic conditions chosen above:

$$\underset{*(b)}{E} = E / U_{b.N}, \tag{2.4}$$

or

$$\underset{*(b)}{E} = \underset{*(rated)}{E} \frac{U_{rated}}{U_{b.N}}, \tag{2.5}$$

$$\underset{*(b)}{\underline{Z}} = \underline{Z}_{(rated)} \frac{S_b}{U_{b.N}{}^2}, \tag{2.6}$$

or

$$\underset{*b}{\underline{Z}} = \underset{*(rated)}{\underline{Z}} \frac{S_b}{S_{rated}} \frac{U_{rated}{}^2}{U_{b.N}{}^2}, \tag{2.7}$$

Where,

$U_{b.N}$ – transforming element's basic voltage level.

Formulas 2.4 and 2.6 should be used when the value of electromotive force and impedance of element are given in absolute units. Formulas 2.5 and 2.7 should be used when the value of electromotive force and impedance of element are given in relative units regarding rated values.

Usually impedances of power lines, cables and reactors are given in absolute units, but impedances of synchronous generators and compensators are given in relative units refereed to rated values.

2.2.3 Using absolute units with transformation according to rough transformer ratios

If actual transformers rated voltages are known, then we should use them to calculate transformer ratios. Sometimes, there is no information about some transformers or autotransformers in the network. In this case the GOST allows using the special average rated voltages instead of rated voltages. For that reason, the GOST states special row of average rated voltages, in kV: 0,23; 0,4; 0,525; 0,69; 3,15; 6,3; 10,5; 13,8; 15,75; 20; 24; 37; 115; 230; 340; 515; 770; 1175.

If we want to represent elements of the network using absolute units and transform them to some basic voltage level using rough transformer ratios, these formulas can be used:

$$\overset{\circ}{E} = E \frac{U_{av.fault}}{U_{av.N}}, \qquad \overset{\circ}{\underline{Z}} = \underline{Z} \frac{U_{av.fault}^{2}}{U_{av.N}^{2}} \tag{2.8}$$

Where,

$U_{av.fault}$ – an average rated voltage of the fault's place;

$U_{av.N}$ – transforming element's average voltage level.

If electromotive force or impedance of some element is known in relative units refereed to rated conditions, then we can represent them in absolute units using rough transformers ratios by means of these formulas:

$$\overset{\circ}{E} = E_{*(rated)} \cdot U_{av.fault}, \qquad \overset{\circ}{\underline{Z}} = \underline{Z}_{*(rated)} \cdot \frac{U_{av.fault}^{2}}{S_{rated}} \tag{2.9}$$

2.2.4 Using relative units with transformation according to rough transformer ratios

If we want to represent elements of the network using relative units and transform them to some basic voltage level using rough transformer ratios, we should arbitrarily pick the basic apparent power and choose as a basic voltage level, not the rated, but the average voltage level of some transformation step. In this case, the electromotive force and impedance of elements can be found like this:

$$E_{*(b)} = E / U_{av.N}, \tag{2.10}$$

or

$$E_{*(b)} = E_{*(rated)}, \tag{2.11}$$

$$\underline{Z}_{*(b)} = \underline{Z}_{(rated)} \frac{S_b}{U_{av.N}^{2}}, \tag{2.12}$$

or

$$\underset{*}{Z}_{b} = \underset{*}{Z}_{(rated)} \frac{S_b}{S_{rated}} \quad , \qquad (2.13)$$

2.3 Models of the power system elements

2.3.1 Upstream network

If an electrical installation is fed from the upstream network, the upstream network can be represented as a source of constant voltage with its reactance and source of electromotive force.

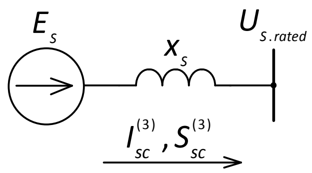


Fig. 2.3 – Model of the upstream network

Parameters of the model are shown in figure 2.3 and can be defined in absolute units as follows:

$$E_S = \frac{U_{S.rated}}{\sqrt{3}}$$
$$x_S = \frac{U_{S.rated}}{\sqrt{3} \cdot I_{SC}^{(3)}} = \frac{U_{S.rated}^2}{S_{SC}^{(3)}} \quad , \qquad (2.14)$$

Where,

$U_{S.rated}$ – average rated voltage of the system, kV;

$I_{SC}^{(3)}$, $S_{SC}^{(3)}$ – three-phase short-circuit current and apparent power from the upstream network, kA, MVA respectively.

If there is no any information about short-circuit current from the upstream network, it's possible to use the rated tripping current of the circuit-breakers which are installed on the substation down the upstream network.

The negative sequence reactance of the upstream network can be considered equal to the positive sequence reactance.

The zero sequence reactance can be found using information about the elements of the upstream network (the most important elements here are transformers and especially their winding connections).

2.3.2 Synchronous machines

There are three types of synchronous machines typically presented in electrical power networks:

1) Synchronous generators;

2) Synchronous motors;

3) Synchronous compensators.

Models of these machines are presented in figures 2.4, 2.5 and 2.6 respectively.

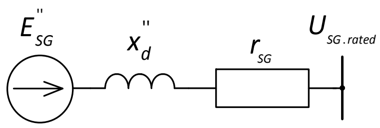


Fig. 2.4 – Model of the synchronous generator

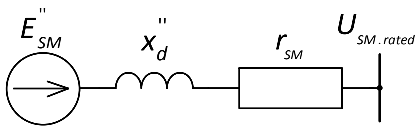


Fig. 2.5 – Model of the synchronous motor

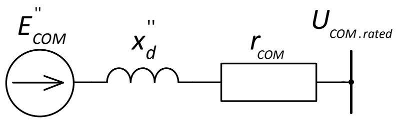


Fig. 2.6 – Model of the synchronous compensator

As seen in figures, models of synchronous machines are pretty similar and consist of subtransient electromotive force source, subtransient reactance and resistance of machine's stator.

Subtransient electromotive force for synchronous generators and motors with rated voltage below 1 kV can be calculated using formula 2.15 and for ones with rated voltage above 1 kV using formula 2.16. For synchronous compensators with rated voltage above 1 kV formula 2.17 can be used :

$$E''_{SG/SM} = \sqrt{(U_{(0)} \cdot \cos\varphi_{(0)} + I_{(0)} \cdot r_{SG/SM})^2 + (U_{(0)} \cdot \sin\varphi_{(0)} \pm I_{(0)} \cdot x''_d)^2}\ , \qquad (2.15)$$

$$E''_{SG/SM} = \sqrt{(U_{(0)} \pm I_{(0)} \cdot x''_d \cdot \sin\varphi_{(0)})^2 + (I_{(0)} \cdot x''_d \cdot \cos\varphi_{(0)})^2}\ , \qquad (2.16)$$

$$E''_{COM} = U_{(0)} \pm I_{(0)} \cdot x''_d\, , \qquad (2.17)$$

Where,

$U_{(0)}$ – phase voltage on the terminals of the generator or motor in the moment prior to the short-circuit fault, V;

$I_{(0)}$ – current flowing through the stator in the moment prior to the short-circuit fault, A;

$\varphi_{(0)}$ – phase shift angle between voltage and current in the moment prior to the short-circuit fault, el.deg;

$r_{SG/SM}$ – resistance of machine's stator, Ω;

x''_d – subtransient reactance of the synchronous machine, Ω.

In the formulas 2.15, 2.16 and 2.17 symbol "+" refers to machines worked in overexcitation mode prior to the short-circuit state, symbol "-" refers to machines worked in underexcitation mode of operation.

In case of synchronous machines with rated voltage below 1 kV, we have to take into account the stator's resistance and the subtransient reactance of the synchronous machine. Usually, the machine's datasheet contains information about these parameters. If it doesn't, the GOST allows us to use approximate data:

$$\begin{aligned} x''_{*d} &= 0{,}15; \\ r_{SM} &= 0{,}15 \cdot x''_d \end{aligned}, \qquad (2.18)$$

Important to mention that usually the resistance of the synchronous machine is given in the reference to some temperature which is different from the working temperature. Formula 2.19 allows transforming the value of stator's resistance with respect to the working temperature:

$$r_{\vartheta w} = r_{\vartheta 0} \cdot \frac{235 + \vartheta_w}{235 + \vartheta_0}, \qquad (2.19)$$

Where,

$r_{\vartheta 0}$ - stator's resistance from a datasheet referred to the temperature ϑ_0 (usually $\vartheta_0 = 15\,^{\circ}C$);

$r_{\vartheta w}$ - stator's resistance value referred to the working temperature ϑ_w.

In case of synchronous machines with rated voltage above 1 kV, in approximate calculations, it's possible not to take into account the stator's resistance of a synchronous machine.

In case of calculation of the aperiodic component of the short-circuit current, a synchronous machine should be represented by its stator's resistance and negative sequence stator's reactance.

For synchronous machines with the rated voltage below 1 kV, the GOST allows using simplification:

$$x_2 = x''_d, \qquad (2.20)$$

If a datasheet doesn't contain information about negative sequence stator reactance or stator's resistance, the GOST presents a special formula which connects these parameters with a time constant of an aperiodic component of the three-phase short-circuit current decaying with the angular frequency of the voltage:

$$r_{*SM(rated)} = \frac{x_{*2(rated)}}{w \cdot T_a^{(3)}}, \qquad (2.21)$$

Where,

$r_{*SM(rated)}$ – stator resistance in relative units with respect to the rated values;

$x_{*2(rated)}$ – negative sequence stator reactance in relative units with respect to the rated values;

$T_a^{(3)}$ – time constant of the aperiodic component of the three-phase short-circuit current decaying, s;

w – angular frequency of the voltage, rad/s.

Information about zero sequence reactance of the synchronous machine can be found in the datasheet.

2.3.3 Asynchronous machines

The equivalent model of an asynchronous motor is shown in figure 2.7.

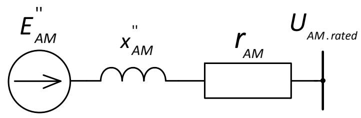


Fig. 2.7 – Model of the asynchronous motor

The model of the asynchronous motor consists of the motor's subtransient electromotive force, subtransient reactance and resistance.

Subtransient electromotive force for motors with the rated voltage below and above 1 kV can be calculated using formulas 2.22 and 2.23 respectively:

$$E''_{AM} = \sqrt{(U_{(0)} \cdot \cos\varphi_{(0)} - I_{(0)} \cdot r_{AM})^2 + (U_{(0)} \cdot \sin\varphi_{(0)} - I_{(0)} \cdot x''_{AM})^2}\ , \qquad (2.22)$$

$$E''_{AM} = \sqrt{(U_{(0)} - I_{(0)} \cdot x''_{AM} \cdot \sin\varphi_{(0)})^2 + (I_{(0)} \cdot x''_{AM} \cdot \cos\varphi_{(0)})^2}\ , \qquad (2.23)$$

Where,

$U_{(0)}$ – phase voltage on the terminals of the motor in the moment prior to the short-circuit fault, V;

$I_{(0)}$ – current flowing through the stator in the moment prior to the short-circuit fault, A;

$\varphi_{(0)}$ – phase shift angle between voltage and current in the moment prior to the short-circuit fault, el.deg;

r_{AM} – resistance of the motor, Ω;

x''_{AM} – subtransient reactance of the motor, Ω.

For calculation of the initial symmetrical short-circuit current, the GOST states for motors with rated voltage below 1 kV to take into account both the subtransient reactance and the motor's resistance:

$$r_{AM} = r_1 + 0{,}96 \cdot \overset{\circ}{r}_2\ , \qquad (2.24)$$

Where,

r_1 – motor's stator resistance, mΩ:

$$r_1 = \frac{s_{rated} \cdot U^2_{rated} \cdot \cos\varphi_{rated}}{P_{rated}}\ , \qquad (2.25)$$

$\overset{\circ}{r}_2$ – motor's rotor resistance transformed to the stator, mΩ:

$$\overset{\circ}{r}_2 = \frac{0{,}36 \cdot \underset{*}{M_L} \cdot (P_{rated} + P_{mech.loss})}{\underset{*}{I^2_L} \cdot I^2_{rated} \cdot (1 - s_{rated})}\ , \qquad (2.26)$$

s_{rated} – rated slip of the motor in relative units;

U_{rated} – rated linear voltage of the motor, V;

$\cos\varphi_{rated}$ – rated power factor of the motor in relative units;

P_{rated} – rated active power of the motor, kW;

$\underset{*}{M}_L$ – ratio between locked-rotor torque and rated torque of the motor in relative units;

$P_{mech.loss}$ – mechanical losses of the motor including additional losses, kW;

$\underset{*}{I}_L$ – ratio between locked-rotor current and rated current of the motor in relative units;

I_{rated} – rated current of the motor, A.

A Subtransient reactance of the synchronous motor with the rated voltage below 1 kV can be defined as:

$$x''_{AM} = \sqrt{\left(\frac{U_{rated}}{\sqrt{3} \cdot \underset{*}{I}_L \cdot I_{rated}} \cdot 10^3\right)^2 - r_{AM}^2}\ , \tag{2.27}$$

In case of lack of information about the asynchronous motor with the rated voltage below 1 kV or inability to calculate its parameters using formulas 2.24 - 2.27, the GOST states the subtransient reactance and relation between the subtransient reactance and the resistance of the motor in relative units, which can be used in approximate calculations:

$$\begin{aligned} \underset{*}{x}''_{AM} &= 0,18; \\ r_{AM} &= 0,36 \cdot x''_{AM} \end{aligned}\ , \tag{2.28}$$

For calculation of the initial symmetrical short-circuit current the GOST states for motors with rated voltage above 1 kV to take into account only the subtransient reactance, it can be found using the formula below:

$$x''_{AM} = \frac{1}{\underset{*}{I}_L} \cdot \frac{U_{rated}^2 \cdot \cos\varphi_{rated} \cdot \eta}{P_{rated}}\ , \tag{2.29}$$

Where,

$\underset{*}{I}_L$ – ratio between locked-rotor current and rated current of the motor in relative units;

U_{rated} – rated linear voltage of the motor, kV;

$\cos\varphi_{rated}$ – rated power factor of the motor in relative units;

P_{rated} – rated active power of the motor, MW.

In case of calculation of the aperiodic component of the short-circuit current, asynchronous motors should be represented by the negative sequence reactance (which GOST allows to consider equal to subtransient reactance if there is no any information about the real value of the negative sequence reactance) and the stator resistance, which for motors with the rated voltage below 1 kV can be defined according to the formula 2.25 and for the motor with the rated voltage above 1 kV can be defined in Ω using formula 2.30:

$$r_1 = s_{rated} \cdot \eta \cdot \frac{U_{rated}^2 \cdot \cos\varphi_{rated}}{P_{rated}}\ , \tag{2.30}$$

Where,

s_{rated} – rated slip of the motor in relative units;

η – efficiency of the motor in relative units;

U_{rated} – rated linear voltage of the motor, kV;

$\cos\varphi_{rated}$ – rated power factor of the motor in relative units;

P_{rated} – rated active power of the motor, MW.

Information about the negative and zero sequence impedance of the asynchronous motor can be found in the motor's datasheet.

2.3.4 Complex load

A Complex load consists of asynchronous motors (AM), converters (C), electrothermal installations (TH), incandescent (IL) and gas-filled lamps (GL). As a node with a complex load has rotating machines, these machines can feed the place of fault.

The model of the complex load is depicted in figure 2.8. It consists of the complex impedance and transient electromotive force.

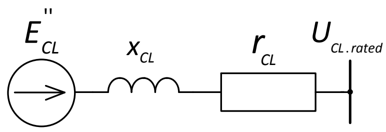
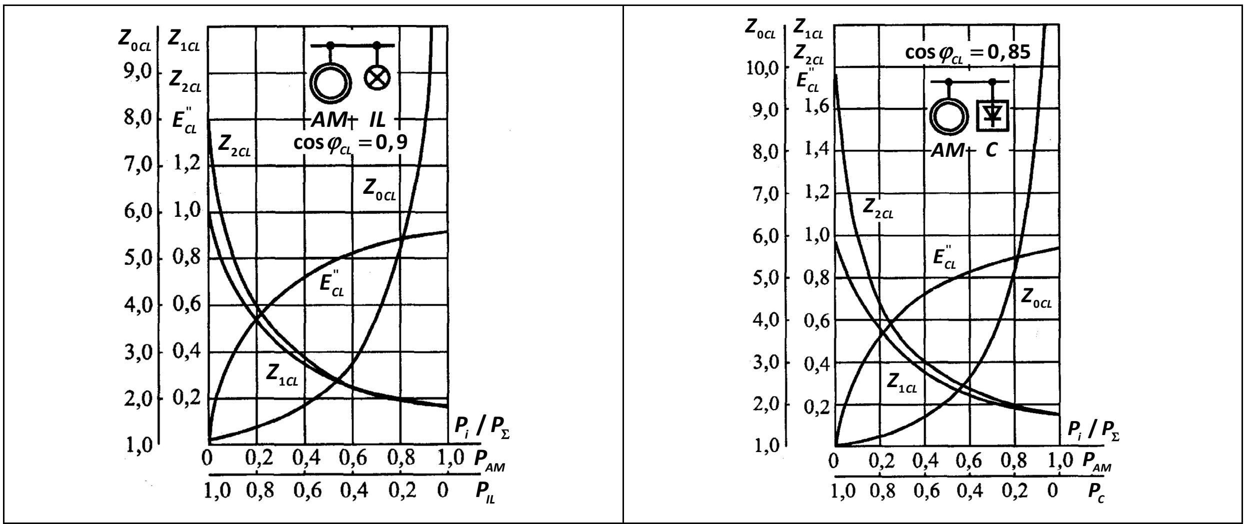


Fig. 2.8 – Model of the complex load

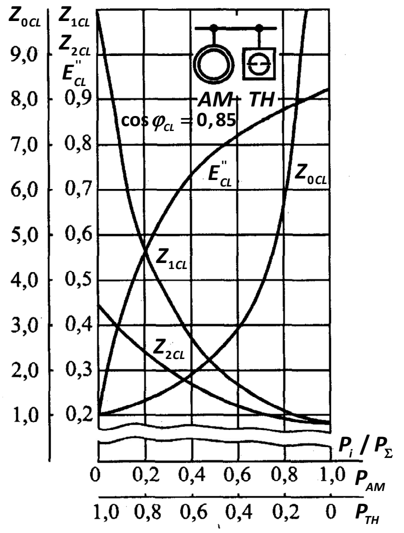
If the consumer list doesn't contain enough information about the complex load, then approximate data about equivalent positive, negative and zero sequence impedances, power factor and transient electromotive force of the complex load with the rated voltage below 1 kV can be found using curves from the figure 2.9.



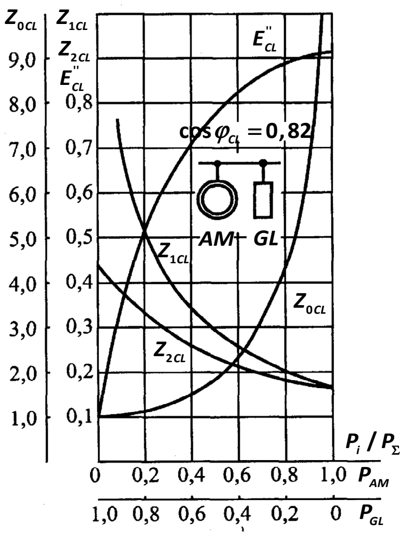
A	B

Fig.2.9 – Dependencies of the complex load's parameters from its structure

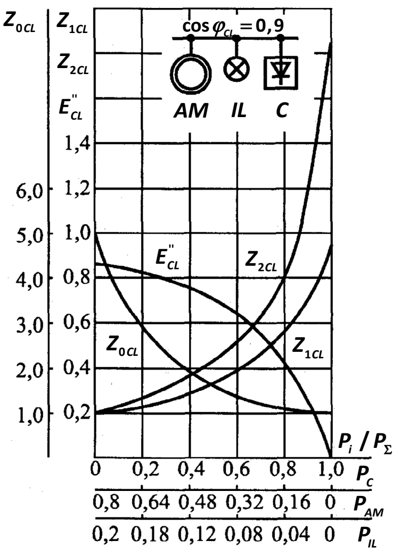
Continuation of Fig.2.9



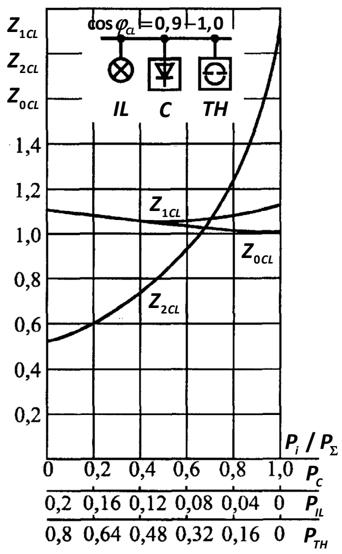
C



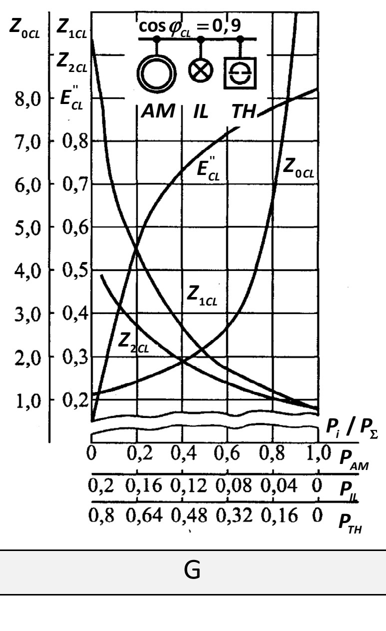
D



E



F



G

Typical parameters of some elements of the complex load are collected in table 2.1. Using them and formula 2.31, it's possible to calculate the whole impedance of the complex load in relative units refereed to rated values:

$$z_{1CL(rated)} = S_{\Sigma} \frac{1}{\sum_{i=1}^{n} \frac{S_i}{\sqrt{r_{1i}^2 + x_{1i}^2}}}, \tag{2.31}$$

Where,

r_{1i} and x_{1i} – active and reactive components of the equivalent complex impedance of i-th consumer in relative units, including the impedance which links a consumer and busbars. Values of these parameters can be found in table 2.1;

S_i – apparent power of the i-th consumer in the complex load, kVA;

S_{Σ} – total apparent power of the whole complex load, kVA.

Table 2.1 – Equivalent circuit's parameters of the complex load

Type of consumer	E''_{CL}	cos φ	Complex impedance, r.u.	
			Z_{1CL}	Z_{2CL}
Synchronous motors, $U_n > 1\text{kV}$	1,074	0,9	0,04 + *j*0,15	0,04 + *j*0,15
Synchronous motors, $U_n < 1\text{kV}$	1,079	0,9	0,03 + *j*0,16	0,03 + *j*0,16
Asynchronous motors, $U_n > 1\text{kV}$	0,93	0,87	0,01 + *j*0,17	0,01 + *j*0,17
Asynchronous motors, $U_n < 1\text{kV}$	0,9	0,8	0,07 + *j*0,18	0,07 + *j*0,18
Incandescent lamps	0	1,0	1,0	1,33
Gas-filled lamps	0	0,85	0,85 + *j*0,53	0,382 + *j*0,24
Converters	0	0,9	0,9 + *j*0,45	1,66 + *j*0,81
Electro-thermal installations	0	0,9	1 + *j*0,49	0,4 + *j*0,2

There are some cases when there is no need to take a complex load into account:

1) For nodes with the rated voltage below 1 kV, If the sum of the electrical motor's rated currents is lower than 1 % of the initial symmetrical short-circuit current calculated without complex load;

2) For nodes with the rated voltage above 1 kV, If the current from complex load in case of fault is lower than 5 % of the initial symmetrical short-circuit current calculated without complex load.

2.3.5 Overhead lines

An overhead line according to the GOST is represented by its resistance and reactance, see figure 2.9.

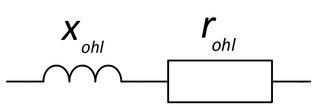


Fig. 2.10 – Model of the power line

Usually, conductor datasheets contain the resistance per unit of length, so the resistance of the overhead line can be calculated using the formula:

$$r_{ohl} = r_{p.u.} \cdot l_{ohl}, \tag{2.32}$$

Where,

$r_{p.u.}$ – resistance per unit length of the overhead line, Ω/m;

l_{ohl} – length of the overhead line, m.

A value of the overhead line's positive sequence reactance per unit of the length according to the GOST should be either taken from special reference tables in accordance with the material of the line, cross-section of the wires and an average distance between phases or can be calculated using formulas from [4]:

$$x_{p.u.} = 0{,}145 \cdot \lg \frac{D_e}{\rho_{eqv.w}}, \tag{2.33}$$

Where,

D_e – equivalent depth of the return wire location, usually the value of 1000 m is used;

$\rho_{eqv.w}$ – equivalent radius of the conductor with respect to skin effect, m;

$$\rho_{eqv.w} = \sqrt[w]{k \cdot \rho_w \cdot a_{av}^{w-1}}, \tag{2.34}$$

Where,

k – special coefficient which depends on the material of a wire and its structure. Usually, it is considered to be equal to 0,9.

ρ_w – real radius of the conductor, m;

w – number of subconductors per phase;

a_{av} – geometric mean of distances between subconductors in one phase;

$$a_{av} = \sqrt[\frac{w(w-1)}{2}]{\begin{matrix}\text{product of all possible distances} \\ \text{between subconductors}\end{matrix}}, \tag{2.35}$$

If there is only one phase conductor, formula 2.34 can be simplified to 2.36:

$$\rho_{eqv.w} = k \cdot \rho_w, \tag{2.36}$$

Therefore, the reactance of the overhead line can be calculated using the formula:

$$x_{ohl} = x_{p.u.} \cdot l_{ohl}, \tag{2.37}$$

Where,

$x_{p.u.}$ – reactance per unit length of the overhead line, Ω/m;

l_{ohl} – length of the overhead line, m.

The negative sequence impedance of the overhead line according to the GOST is equal to the positive sequence impedance.

The zero sequence impedance of the overhead line depends on the cross-sections of wires, distance between phases, presence of earth-wire and other overhead lines lying in the same route that's why it should be calculated for each construction of the overhead line individually. The approach of calculation of the zero sequence impedance for the overhead lines with the most common types of the structure according to [4] is defined below.

For a **single circuit line without earth wire** the zero sequence impedance can be calculated as follows:

$$z_0 = r_{ohl} + 0,15 + j \cdot 0,435 \lg \frac{D_e}{\rho_{av}}, \tag{2.38}$$

Where,

ρ_{av} – average geometric mean of distances between phase wires, m:

$$\rho_{av} = \sqrt[3]{\rho_{eqv.w} \cdot D_{av}^2}, \tag{2.39}$$

Where,

D_{av} – geometric mean of distances between phase wires, m:

$$D_{av} = \sqrt[3]{D_{AB} \cdot D_{BC} \cdot D_{AC}}, \tag{2.40}$$

For a **single circuit line with one earth wire** the zero sequence impedance can be calculated as follows:

$$z_0^{e.w.} = z_0 - \frac{z_{0w/e.w.}^2}{z_{0e.w.}}, \tag{2.41}$$

Where,

z_0 – zero sequence impedance calculated using formula 2.36, Ω;

$z_{0w/e.w.}$ – mutual induction impedance between phase wires and earth wire, Ω;

$$z_{0w/e.w.} = 0,15 + j \cdot 0,435 \lg \frac{D_e}{D_{w/e.w.}}, \tag{2.42}$$

Where,

$D_{w/e.w.}$ – geometric mean of distance from each phase wire to earth wire, m:

$$D_{w/e.w.} = \sqrt[3]{D_{A/e.w.} \cdot D_{B/e.w.} \cdot D_{A/e.w}}, \tag{2.43}$$

$z_{0e.w.}$ – zero sequence impedance of the earth wire, Ω:

$$z_{0e.w.} = 3r_{e.w.} + 0,15 + j \cdot 0,435 \lg \frac{D_e}{\rho_{eqv.e.w.}}, \tag{2.44}$$

Where,

$r_{e.w.}$ – resistance of the earth wire, Ω;

$\rho_{eqv.e.w.}$ – equivalent radius of the earth wire, m:

$$\rho_{eqv.e.w.} = 0{,}9 \cdot \rho_{e.w.}, \quad (2.45)$$

Where,

$\rho_{e.w.}$ – real radius of the earth wire, m.

For a **single circuit line with two earth wires** the zero sequence impedance can be calculated as follows:

$$z_0^{2e.w.} = z_0 - \frac{z_{0w/eqv.e.w.}^2}{z_{0eqv.e.w.}}, \quad (2.46)$$

Where,

z_0 – zero sequence impedance calculated using formula 2.38, Ω;

$z_{0w/eqv.e.w.}$ – mutual induction impedance between phase wires and an equivalent earth wire, Ω;

$$z_{0w/eqv.e.w.} = 0{,}15 + j \cdot 0{,}435 \lg \frac{D_e}{D_{w/eqv.e.w.}}, \quad (2.47)$$

Where,

$D_{w/eqv.e.w.}$ – geometric mean of the distance from each phase wire to the equivalent earth wire, m:

$$D_{w/eqv.e.w.} = \sqrt[6]{D_{A/e.w.1} \cdot D_{B/e.w.1} \cdot D_{A/e.w.1} \cdot D_{A/e.w.2} \cdot D_{B/e.w.2} \cdot D_{A/e.w.2}}, \quad (2.48)$$

$z_{0eqv.e.w.}$ – zero sequence impedance of the equivalent earth wire, Ω:

$$z_{0eqv.e.w.} = 1{,}5 r_{e.w.} + 0{,}15 + j \cdot 0{,}435 \lg \frac{D_e}{\sqrt{\rho_{eqv.e.w.} \cdot D_{e.w.1.2.}}}, \quad (2.49)$$

Where,

$r_{e.w.}$ – resistance of the earth wire, Ω;

$\rho_{eqv.e.w.}$ – equivalent radius of the earth wire, can be defined using formula 2.45;

$D_{e.w.1.2.}$ – distance between earth wires, m.

For **Double circuit line without an earth wire** the zero sequence impedance can be calculated as follows:

$$z_0^{'} = z_0 + z_{0I/II}, \quad (2.50)$$

Where,

z_0 – zero sequence impedance calculated using formula 2.38, Ω;

$z_{0I/II}$ – zero sequence impedance of the mutual induction between two circuits, Ω:

$$z_{0I/II} = 0{,}15 + j \cdot 0{,}435 \lg \frac{D_e}{D_{I/II}}, \quad (2.51)$$

Where,

$D_{I/II}$ – geometric mean of the distances between phases of two circuits, m:

$$D_{I/II} = \sqrt[9]{D_{Aa} \cdot D_{Ab} \cdot D_{Ac} \cdot D_{Ba} \cdot D_{Bb} \cdot D_{Bc} \cdot D_{Ca} \cdot D_{Cb} \cdot D_{Cc}}\ , \tag{2.52}$$

For **double circuit line with two earth wires** the zero sequence impedance for both circuits can be calculated as follows:

$$z_{0I}^{2e.w.} = z_{0I/I} - \frac{z_{0I/eqv.e.w.}^2}{z_{0eqv.e.w.}}\ , \tag{2.53}$$

$$z_{0II}^{2e.w.} = z_{0II/II} - \frac{z_{0II/eqv.e.w.}^2}{z_{0eqv.e.w.}}\ , \tag{2.54}$$

Where,

$z_{0I/I}$, $z_{0II/II}$ – zero sequence impedance calculated using formula 2.38, Ω;

$z_{0I/eqv.e.w.}$, $z_{0I/eqv.e.w.}$ – mutual induction impedance between phase wires and the equivalent earth wire, can be calculated using formula 2.47;

$z_{0eqv.e.w.}$ – zero sequence impedance of the equivalent earth wire, can be calculated using formula 2.49.

In approximate calculations it's allowed to use average zero sequence to positive sequence impedance ratios, see table 2.2:

Table 2.2 – Ratios between zero sequence and positive sequence impedance of the most common types of overhead lines

Type of power line's construction	x_0/x_1
Single circuit line without an earth wire	3,5
Single circuit line with earth wires made of steel	3,0
Single circuit line with earth wires made of materials with high conductivity	2,0
Double circuit line without an earth wire	5,5
Double circuit line with earth wires made of steel	4,7
Double circuit line with earth wires made of materials with high conductivity	3,0

2.3.6 Cables

Model of a cable line consists of the cable's resistance and reactance, figure 2.10.

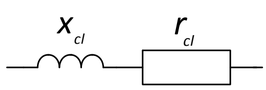


Fig. 2.11 – Model of the cable line

Usually, a datasheet of a cable contains information about positive and zero sequence resistance and reactance of a cable per unit of length, so using these parameters and length of a cable we can calculate the whole resistance and reactance of each sequence with help of formulas 2.55:

$$\begin{aligned} r_{1cl} &= r_{1p.u.} \cdot l_{cl} \\ x_{1cl} &= x_{1p.u.} \cdot l_{cl} \\ r_{0cl} &= r_{0p.u.} \cdot l_{cl} \\ x_{0cl} &= x_{0p.u.} \cdot l_{cl} \end{aligned}, \qquad (2.55)$$

The negative sequence impedance of the cable line according to the GOST is equal to the positive sequence impedance.

If there is no information about cable's zero sequence complex impedance per unit of length, in approximate calculation the GOST allows using these ratios between the positive sequence and the zero sequence complex impedance:

$$\begin{aligned} r_{0cl} &= 10 \cdot r_{1cl} \\ x_{0cl} &= (3,5-4,5) \cdot x_{1cl} \end{aligned}, \qquad (2.56)$$

2.3.7 Transformers and autotransformers

The model of a **two-winding transformer** consists of transformer resistance and reactance, figure 2.11.

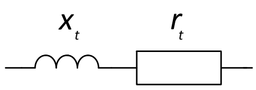


Fig. 2.12 – Model of the two winding transformer

Transformer's parameters can be calculated in relative units refereed to rated values using formulas below:

$$\begin{aligned} z_{*t(rated)} &= \frac{u_k}{100} \\ r_{*t(rated)} &= \frac{\Delta P_{SC}}{S_{rated}} \cdot 10^3 \\ x_{*t(rated)} &= \sqrt{z^2_{*t(rated)} - r^2_{*t(rated)}} \end{aligned}, \qquad (2.57)$$

Where,

u_k – short-circuit voltage of the transformer, %;

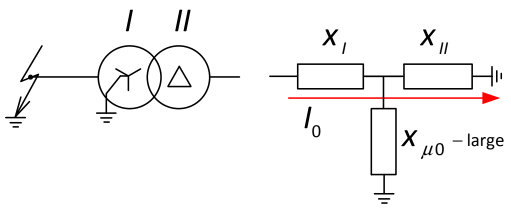
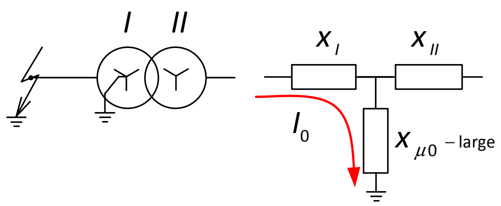
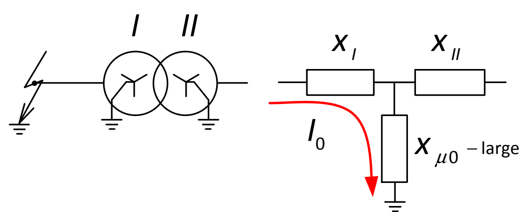
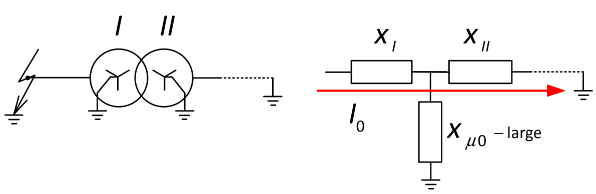
ΔP_{SC} – total losses of the transformer in the windings at rated current, kW;

S_{rated} – rated apparent power of the transformer, MVA.

Parameters of the negative sequence equivalent circuit for any transformer according to the GOST are the same as for the positive sequence circuit.

Parameters of the zero sequence equivalent circuit of the two-winding transformer can be derived from a datasheet of the transformer. To understand the behavior of the transformer with different types of winding connection, in case of zero sequence current flows through it refer to table 2.3.

Table 2.3 – Examples of the transformers with a different type of winding connection behavior in case of zero sequence current flows through it

Type of windings connection	Zero sequence impedance of transformer, Ω
	$x_{t0} = x_I + x_{II}$
	$x_{t0} = x_I + x_{\mu 0} \approx \infty$
	$x_{t0} = x_I + x_{\mu 0} \approx \infty$
	$x_{t0} = x_I + x_{II}$

The model of the **three-winding transformer** or **autotransformer with low voltage winding** consists of the resistance and the reactance of each winding. These parameters can be calculated in relative units refereed to rated values using formulas 2.58, 2.59.

$$\left.\begin{aligned}
x_{*HV(rated)} &= \frac{u_{kHV}}{100} = 0,5(u_{kHV-LV} + u_{kHV\text{-}MV} - u_{kMV\text{-}LV});\\
x_{*MV(rated)} &= \frac{u_{kMV}}{100} = 0,5(u_{kHV-MV} + u_{kMV-LV} - u_{kHV-LV});\\
x_{*LV(rated)} &= \frac{u_{kLV}}{100} = 0,5(u_{kHV-LV} + u_{kMV-LV} - u_{kHV-MV}),
\end{aligned}\right\}, \qquad (2.58)$$

$$\left.\begin{aligned}
r_{*HV(rated)} &= \frac{0,5\cdot 10^3}{S_{rated}}(\Delta P_{kHV-MV} + \Delta P_{kHV-LV} - \Delta P_{kMV-LV});\\
r_{*MV(rated)} &= \frac{0,5\cdot 10^3}{S_{rated}}(\Delta P_{kHV-MV} + \Delta P_{kMV-LV} - \Delta P_{kHV-LV});\\
r_{*LV(rated)} &= \frac{0,5\cdot 10^3}{S_{rated}}(\Delta P_{kHV-LV} + \Delta P_{kMV-LV} - \Delta P_{kHV-MV});
\end{aligned}\right\}, \qquad (2.59)$$

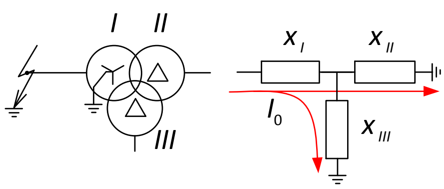
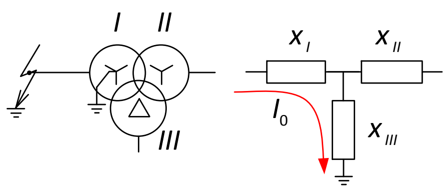
Where,

u_{kHV-LV}, $u_{kHV\text{-}MV}$, $u_{kMV\text{-}LV}$ – short-circuit voltages of the transformer, %;

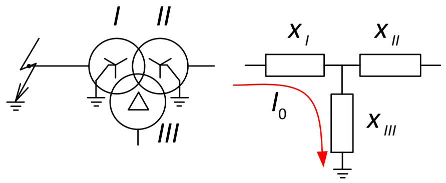
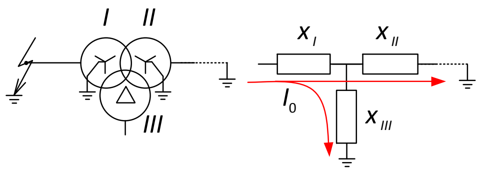
ΔP_{kHV-MV}, ΔP_{kHV-LV}, ΔP_{kMV-LV} – losses in the transformer's windings at rated current, kW.

Parameters of the zero sequence equivalent circuit of the **three-winding transformer** or **autotransformer with low voltage winding** can be derived from its datasheet. To understand the behavior of the transformer with different types of winding connection, in case of zero sequence current flows through it refer to table 2.4.

Table 2.4 – Examples of the transformers with a different type of winding connection behavior in case of zero sequence current flows through it

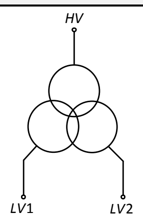
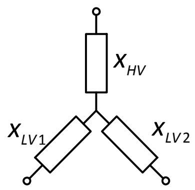
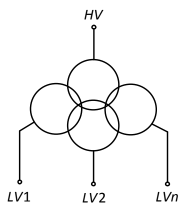
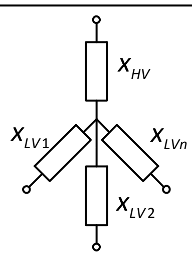
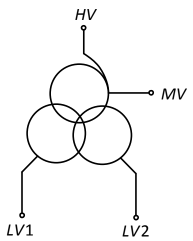
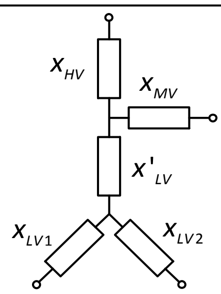
Type of windings connection	Zero sequence impedance of transformer, Ω
	$x_{t0} = x_I + \frac{x_{II}\cdot x_{III}}{x_{II} + x_{III}}$
	$x_{t0} = x_I + x_{III}$

Continuation of table 2.4

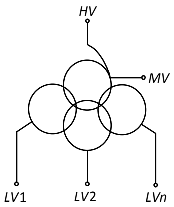
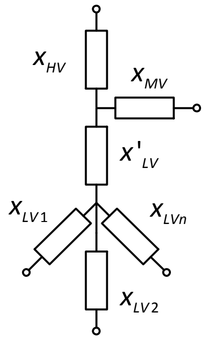
Type of windings connection	Zero sequence impedance of transformer, Ω
	$x_{t0} = x_I + x_{III}$
	$x_{t0} = x_I + \dfrac{x_{II}\cdot x_{III}}{x_{II}+x_{III}}$

Positive sequence equivalent circuits for **other types of transformers** and formulas to calculate their parameters are shown in table 2.5

Table 2.5 – positive sequence equivalent circuits of transformers

Type	Symbol	Equivalent circuit	Formulas
Two-winding transformer with bundled into 2 branches low-voltage winding			$x_{*HV} = 0{,}01\cdot(u_{kHV-LV} - 0{,}25\cdot u_{kLV1-LV2})$ $x_{*LV1} = x_{*LV2} = 0{,}005\cdot u_{kLV1-LV2}$
Two-winding transformer with bundled into *n* branches low-voltage winding			$x_{*HV} = 0{,}01\cdot(u_{kHV-LV} - \dfrac{u_{kLV1-LVn}}{2n})$ $x_{*LV1} = x_{*LV2} = \ldots = x_{*LVn} = 0{,}005\cdot u_{kLV1-LVn}$
Autotransformer with bundled into 2 branches low-voltage winding			$x_{*HV} = 0{,}005(u_{kHV-LV} + u_{kHV\text{-}MV} - u_{kMV\text{-}LV});$ $x_{*MV} = 0{,}005(u_{kHV-MV} + u_{kMV-LV} - u_{kHV-LV});$ $x_{*LV} = 0{,}005(u_{kHV-LV} + u_{kMV-LV} - u_{kHV-MV});$ $x_{*LV1} = x_{*LV2} = 0{,}005\cdot u_{kLV1-LV2};$ $x'_{*LV} = x_{*LV} - 0{,}0025\cdot u_{kLV1-LVn}$

Continuation of table 2.5

Type	Symbol	Equivalent circuit	Formulas
Autotransformer with bundled into *n* branches low-voltage winding			$\underset{*}{x}_{HV} = 0{,}005(u_{kHV-LV} + u_{kHV\text{-}MV} - u_{kMV\text{-}LV});$ $\underset{*}{x}_{MV} = 0{,}005(u_{kHV-MV} + u_{kMV-LV} - u_{kHV-LV});$ $\underset{*}{x}_{LV} = 0{,}005(u_{kHV-LV} + u_{kMV-LV} - u_{kHV-MV});$ $\underset{*}{x}_{LV1} = \underset{*}{x}_{LV2} = \ldots = \underset{*}{x}_{LVn} = 0{,}005 \cdot u_{kLV1-LV2};$ $\underset{*}{x'}_{LV} = \underset{*}{x}_{LV} - 0{,}01 \cdot \frac{u_{kLV1-LVn}}{2n}$

2.3.8 Current limiting reactors

The model of a current limiting reactor consists of its resistance and reactance, figure 2.12.

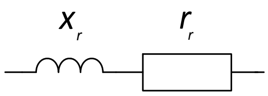


Fig. 2.13 – Model of the current limiting reactor

Usually, a datasheet of the reactor contains these parameters, but if it doesn't the GOST states the way to calculate them in Ω:

$$r_r = \frac{\Delta P_{r.rated}}{I_{r.rated}^2}, \quad x_r = 2 \cdot \pi \cdot f_n \cdot (L - M) \tag{2.60}$$

Where,

$\Delta P_{r.rated}$ – power losses in a phase of the reactor when the rated current is flowing through it, W;

$I_{r.rated}$ – rated current of the reactor, A;

f_n – frequency of the voltage in the network, Hz;

L - inductance of the reactor's coil, H;

M – mutual inductance between phases of the reactor, H.

3. Calculation of the short-circuit currents according to the GOST standard

3.1 General approach to calculation of the short-circuit currents

3.1.1 Initial symmetrical short-circuit current calculation

According to the GOST, the initial symmetrical short-circuit current can be calculated using the formula:

$$\left|I_{S0}^{(n)}\right| = m^{(n)} \cdot \left|I_{SC1}^{(n)}\right|, \tag{3.1}$$

Where,

$m^{(n)}$ – multiplication coefficient which represents the ratio between the initial symmetrical short-circuit current and the positive sequence component of the same short-circuit current, can be found in table 3.1;

(n) – represents the type of the short-circuit fault, for instance, three-phase short-circuit fault is (3), phase-to-earth short circuit fault is (1);

$I_{SC1}^{(n)}$ – the positive sequence component of the short-circuit current, calculated according to the formula:

$$\dot{I}_{SC1}^{(n)} = \frac{\dot{E}_{eq}}{\underline{z}_{1\Sigma} + \Delta\underline{z}^{(n)}}, \tag{3.2}$$

Where,

$\dot{E}_{eq}$ – equivalent phase value of the electromotive force of the short-circuit current source, V;

$\underline{z}_{1\Sigma}$ – equivalent positive sequence impedance from the short-circuit current source to the place of fault, Ω;

$\Delta\underline{z}^{(n)}$ – additive complex impedance, Ω. Formulas to calculate this parameter for a different type of short-circuit fault can be found in table 3.1.

Table 3.1 – Values of the $\Delta\underline{z}^{(n)}$ and $m^{(n)}$ for different types of short-circuit faults

Type of fault	$\Delta\underline{z}^{(n)}$	$m^{(n)}$
Three-phase fault	0	1
Phase-to-phase fault	$\underline{z}_{2\Sigma}$	$\sqrt{3}$
Phase-to-earth fault	$\underline{z}_{2\Sigma} + \underline{z}_{0\Sigma}$	3
Phase-to-phase-to-earth fault	$\dfrac{\underline{z}_{2\Sigma} \cdot \underline{z}_{0\Sigma}}{\underline{z}_{2\Sigma} + \underline{z}_{0\Sigma}}$	$\sqrt{3} \cdot \sqrt{1 - \left\lvert \dfrac{\underline{z}_{2\Sigma} \cdot \underline{z}_{0\Sigma}}{\underline{z}_{2\Sigma} + \underline{z}_{0\Sigma}} \right\rvert}$

3.1.2 Calculation of the symmetrical short-circuit current component at an arbitrary time

<u>Calculation of the symmetrical component of the short-circuit current in arbitrary time from synchronous generators</u>

In complex electrical networks, calculation of the symmetrical component of the short-circuit current should be performed by solving the system of differential equations with help of a computer. In approximate calculations, for generators with the rated voltage below 1 kV the curves from figure 3.1 are used, for generators with the rated voltage above 1 kV and different excitation systems curves from figures 3.2, 3.3 are used. These curves define the change of the symmetrical component of the short-circuit current in time for different fault remoteness. The term remoteness of the short-circuit fault means the ratio of the initial symmetrical short-circuit current to the rated current of the machine:

$$I_{*S0(rated)} = \frac{I_{S0}}{I_{rated}}, \tag{3.3}$$

The symmetrical component of the short-circuit current can be defined as:

$$I_{St} = \gamma_t \cdot I_{S0}, \tag{3.4}$$

Where,

γ_t – the value which can be defined from figures 3.1 – 3.3.

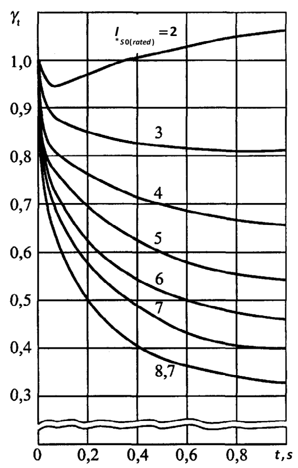
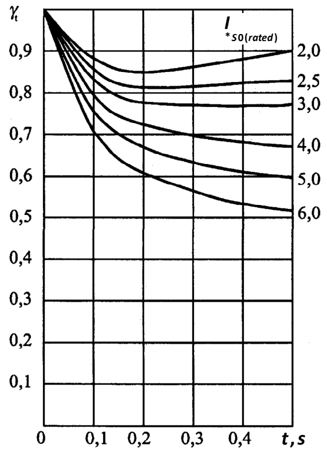
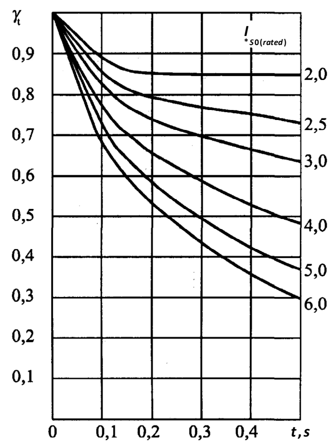


Fig 3.1 – Change of the symmetrical component of the short-circuit current in time from the synchronous generator with the rated voltage below 1 kV



a)



b)

Fig 3.2 – Change of the symmetrical component of the short-circuit current in time from the synchronous generator with the rated voltage above 1 kV and a) independent thyristor excitation system; b) independent thyristor self-excitation system

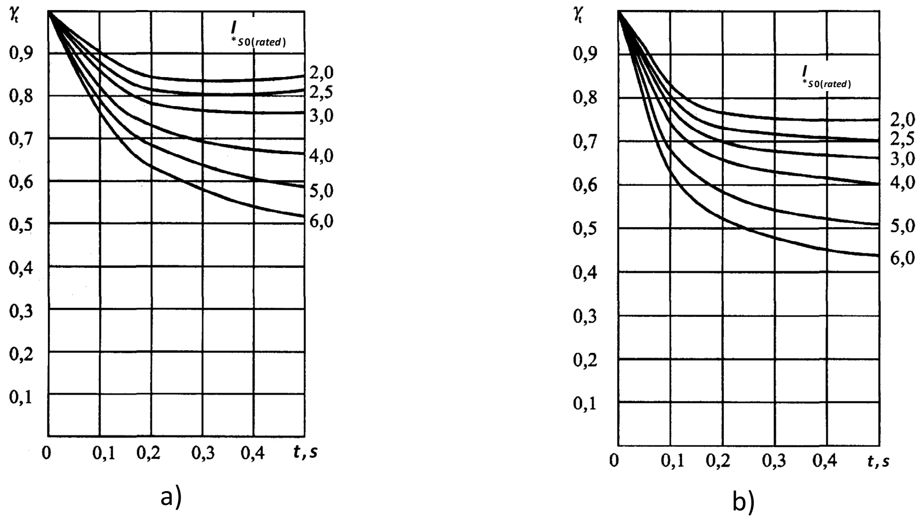


Fig 3.3 – Change of the symmetrical component of the short-circuit current in time from the synchronous generator with the rated voltage above 1 kV and a) diode independent excitation system; b) diode brushless excitation system

<u>Calculation of the symmetrical component of the short-circuit current in arbitrary time from synchronous and asynchronous motors</u>

Accurate calculation of the symmetrical short-circuit current in arbitrary time from asynchronous and synchronous motors can be performed by solving the system of differential equations. In approximate calculations, curves from figure 3.4 for motors with the rated voltage below 1 kV and 3.5 for motors with the rated voltage above 1 kV are used. These curves define the change of the symmetrical component of the short-circuit current in time for different fault remoteness.

$$I_{*S0(rated)} = \frac{I_{S0.AM(SM)}}{I_{AM(SM)rated}}, \tag{3.5}$$

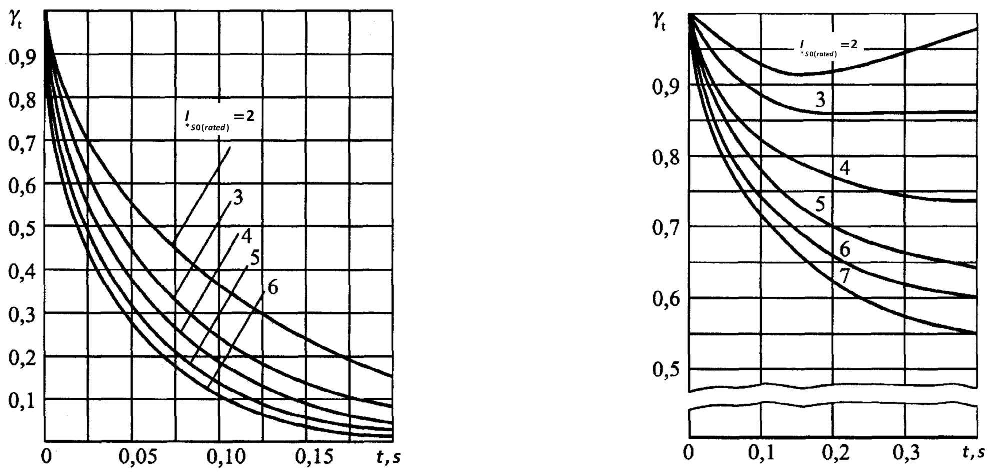
The symmetrical component of the short-circuit current can be defined as:

$$I_{StAM(SM)} = \gamma_t \cdot I_{S0.AM(SM)}, \tag{3.6}$$

Where,

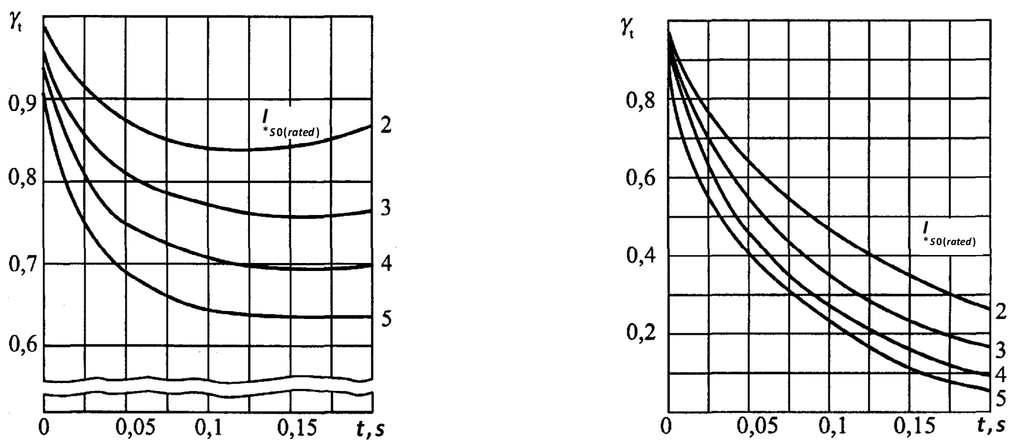
γ_t – the value which can be defined from figures 3.4 and 3.5 for asynchronous and synchronous motors.

The method of special curves takes into account the change of the symmetrical short-circuit current only if the ratio between the initial symmetrical short-circuit current of the machine and its nominal current is equal or higher than 2. If this ratio is lower than 2, it means that the symmetrical short-circuit current is constant in time and doesn't change.



a) b)

Fig 3.4 – Change of the symmetrical component of the short-circuit current in time from the a) asynchronous motor with the rated voltage below 1 kV; b) synchronous motor with the rated voltage below 1 kV



a) b)

Fig 3.5 – Change of the symmetrical component of the short-circuit current in time from the a) synchronous motor with the rated voltage above 1 kV; b) asynchronous motor with the rated voltage above 1 kV

3.1.3 Calculation of the short-circuit current aperiodic component

According to the GOST, the module of the initial aperiodic component of the short-circuit current can be calculated as a difference between instantaneous values of the initial symmetrical short-circuit current and the current flowing at the place of the fault before the fault occurred.

In general, the GOST allows assuming the initial aperiodic short-circuit current as the amplitude of the initial symmetrical short-circuit current:

$$i_{a0} = \sqrt{2} \cdot I_{S0}, \tag{3.7}$$

In the simple, non-meshed networks, where all elements are connected in a series, the aperiodic short-circuit current at the arbitrary moment can be calculated using formula 3.8.

$$i_{at} = i_{a0} \cdot e^{-t/T_a} \ , \tag{3.8}$$

Where,

t – time, s;

T_a – time constant of the aperiodic short-circuit current component decay, s. It can be defined as follows:

$$T_a = \frac{x_\Sigma}{w_n \cdot r_\Sigma} \ , \tag{3.9}$$

Where,

x_Σ and r_Σ – total reactance and resistance of the short-circuit chain, where synchronous generators and motors and asynchronous motors should be represented by the negative sequence stator's reactance and stator's resistance, Ω;

w_n – angular frequency of the network's voltage, rad/s.

If the place of the fault divides the network into radial, independent parts, then aperiodic short-circuits current in the place of fault can be calculated as a sum of aperiodic short-circuit currents flow through each branch:

$$i_{at} = \sum_{i=1}^{m} i_{a0i} \cdot e^{-t/T_{ai}} \ , \tag{3.10}$$

Where,

m – number of independent branches of the network;

i_{a0i} – initial aperiodic short-circuit current of the i-branch, kA;

T_{ai} – time constant of the aperiodic short-circuit current component decay of the i-branch, s.

3.1.4 Calculation of the peak short-circuit current

The peak short-circuit current in the electrical installations with one source of energy (upstream network or synchronous generator) can be calculated by multiplication the initial symmetrical short-circuit current with a peak short-circuit current coefficient and the square root of two:

$$i_p = \sqrt{2} \cdot I_{s0} \cdot K_p \, , \tag{3.11}$$

For the places of fault with the rated voltage below 1 kV, the peak short-circuit current coefficient can be calculated using the formula:

$$K_p = (1 + \sin\varphi_{SC} \cdot e^{-t_p/T_a}) \, , \tag{3.12}$$

Where,

T_a – time constant of the aperiodic short-circuit current component decay, s, which can be defined using formula 3.9.

φ_{SC} – phase shift angle between voltage or electromotive force and the periodic component of the short-circuit current which can be calculated as follows:

$$\varphi_{SC} = arctg(\frac{x_{1\Sigma}}{r_{1\Sigma}}) \, , \tag{3.13}$$

t_p – time period from the beginning of the fault until the occurrence of the peak current, s.

$$t_p = 0{,}01 \cdot \frac{\pi / 2 + \varphi_{SC}}{\pi}, \tag{3.14}$$

For the places of fault with the rated voltage above 1 kV, the peak short-circuit current coefficient can be calculated using one of the following formulas:

$$K_p = 1{,}02 + 0{,}98 \cdot e^{\frac{-3 \cdot r_{1\Sigma}}{x_{1\Sigma}}}, \tag{3.15}$$

$$K_p = 1 + e^{\frac{-0{,}5 \cdot \pi + \varphi_{SC}}{r_{1\Sigma} / x_{1\Sigma}}}, \tag{3.16}$$

If the ratio $\frac{x_{1\Sigma}}{r_{1\Sigma}} \geq 5$, the peak short-circuit current coefficient can be calculated according to the formula:

$$K_p = 1 + e^{\frac{-0{,}01}{T_a}}, \tag{3.17}$$

If the place of the fault divides the network into radial, independent parts then peak short-circuit current in the place of the fault can be calculated as a sum of peak short-circuit currents flowing through each branch.

$$i_p = \sum_{i=1}^{m} \sqrt{2} \cdot I_{S0i} \cdot K_{pi}, \tag{3.18}$$

Where,

m – number of independent branches of the network;

I_{S0i} – initial symmetrical short-circuit current in the i-branch, kA;

K_{pi} – peak short-circuit current coefficient of the i-branch.

For the places of fault with the rated voltage below 1 kV, the peak short-circuit current coefficient of the i-branch can be calculated according to the formula 3.12.

For the places of fault with the rated voltage above 1 kV, the peak short-circuit current coefficient of the i-branch can be calculated according to one of the formulas:

$$K_p = 1{,}02 + 0{,}98 \cdot e^{\frac{-3}{w_n \cdot T_a}}, \tag{3.19}$$

$$K_p = 1 + e^{\frac{-0{,}01 \cdot (0{,}5 + \varphi_{SC} / \pi)}{T_a}}, \tag{3.20}$$

If the ratio $\frac{x_{1\Sigma}}{r_{1\Sigma}} \geq 5$, the peak short-circuit current coefficient can be calculated according to the formula 3.17 as well.

3.2 Specificities of the short-circuit current calculations in the networks with the rated voltage below 1 kV

In case of short-circuit current calculation in the network with the rated voltage below 1 kV GOST 28249-93 states the following assumptions:

1) Use simplification methods if their inaccuracy doesn't exceed 10 %;
2) Simplify the whole network around the short-circuit point and individually consider only autonomous sources of energy and motors with direct junction to that point;
3) Don't consider the magnetic saturation of the electrical machines;
4) Don't consider the transformer's inrush current;
5) Apply the row of average rated voltages and use them to define the transformer's ratio instead of rated voltages given in datasheets;
6) Don't consider the influence of the synchronous, asynchronous motors and complex load if their total rated current doesn't exceed 1% of the initial symmetrical short-circuit current which was calculated without them;
7) Take into account complex impedances of the current transformers, circuit breaker's coils, busbars, resistances of the terminals and arc resistance.

3.3 Specificities of the short-circuit current calculations in the networks with the rated voltage above 1 kV

In case of short-circuit current calculation in the network with the rated voltage above 1 kV GOST R 52735-2007 states the following assumptions:

1) Don't consider EMF's phase shift of the different synchronous machines and deviation of the rotation frequency, if the duration of short-circuit doesn't exceed 0,5 seconds;
2) Don't consider the link between different networks made with help of DC insertion;
3) Don't consider the transverse capacity of overhead power lines with rated voltage 110-220 kV if their length doesn't exceed 200 km, and with rated voltage 330-500 kV if their length doesn't exceed 150 km;
4) Don't consider the magnetic saturation of the electrical machines;
5) Don't consider the transformer's inrush current;
6) Don't consider the active part of the overall short-circuit impedance if it's less than 30% of the inductive part;
7) Roughly consider the decay of the aperiodic component of short-circuit current;
8) Roughly consider loads concentrated on different nodes of the network;
9) Consider that the active part of each impedance is numerically equal to the DC resistance.

4. Description of the used software and its functionality

4.1 Selection of the software

The RastrKZ software is designed to calculate the symmetrical component of the short-circuit current in case of symmetrical or unsymmetrical faults. Short-circuit current calculation methods of this software are based on the following standards:

1) GOST R 52735-2007;

2) GOST 28249-93;

3) RD 153-34.0-20.257-98.

These standards cover the calculation of the short-circuit currents in the networks with the rated voltage below and above 1 kV, so the RastrKZ was chosen as the main software of the thesis.

4.2 Description of the RastrKZ functionality

4.2.1 Calculation of the symmetrical short-circuit current component

Information about the RastrKZ software was obtained from its user manual – [6].

To calculate the symmetrical short-circuit current component RastrKZ uses information about the whole network inserted into the 4 main tables, see figure 4.1:

1) Table of nodes;

2) Table of branches;

3) Table of SC current sources;

4) Table of the fault locations.

These tables are linked to each other by nodes' numbers and fully define the whole network.

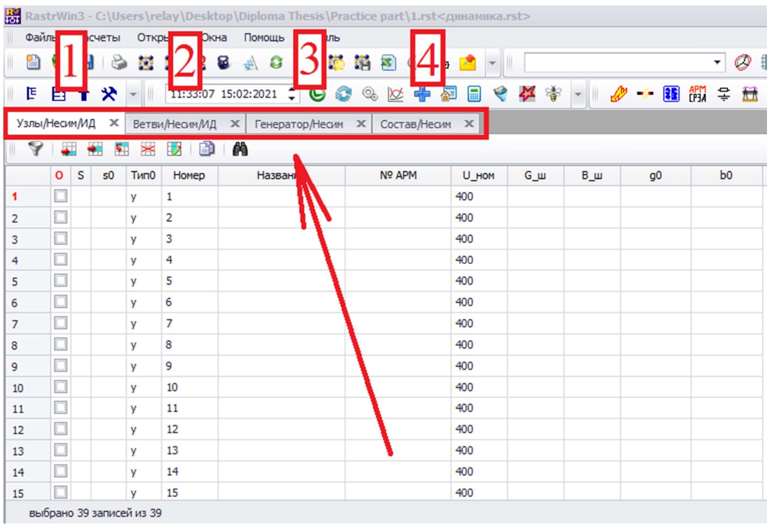


Fig.4.1 – The main window of the RastrKZ software

To use the RastrKZ software, parameters of the network's positive, negative and zero sequence circuits should be defined in advance and the picture of the network with marked nodes' numbers should be performed, see figure 4.2. Parameters should be calculated in absolute units and be transformed to the one voltage level using formula 2.1.

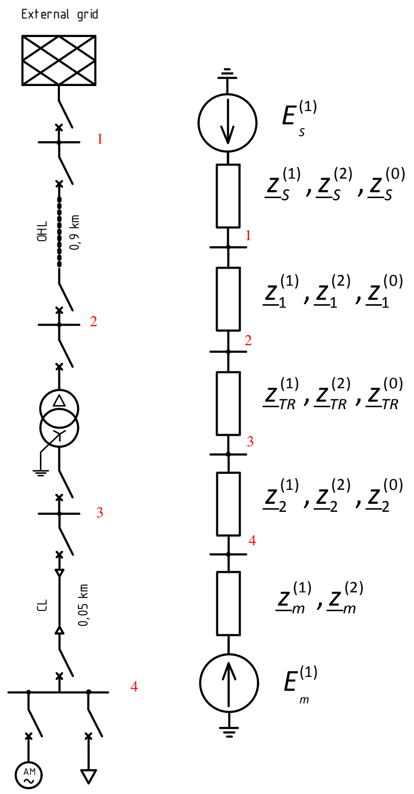
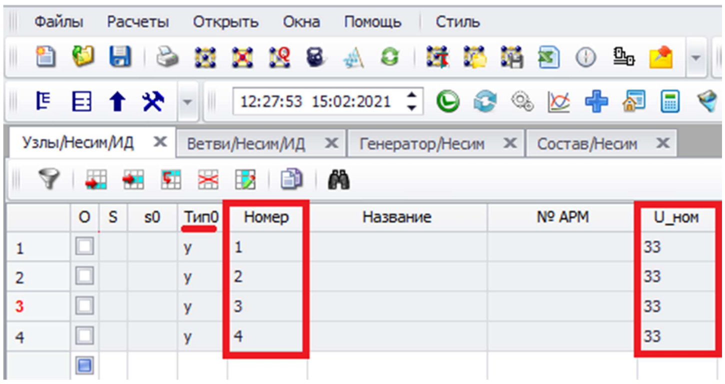


Fig. 4.2 – Preliminary circuit

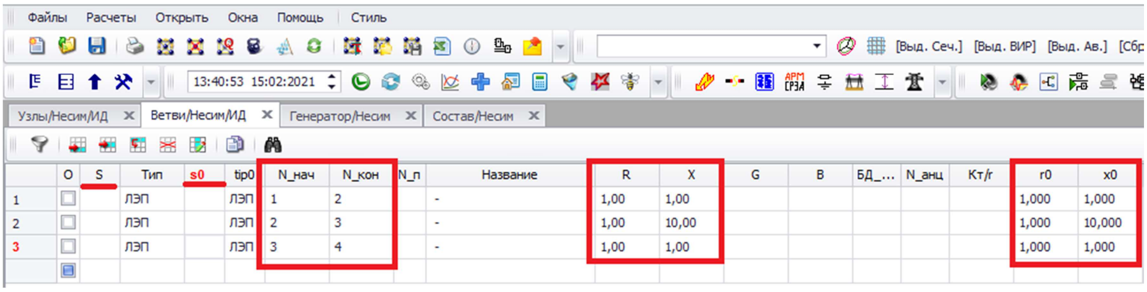
A table of nodes should contain the number of each node from the preliminary circuit and the voltage level parameters of the preliminary circuit were transformed to, see figure 4.3. Also, there is a column named *Type0*. This column allows changing the type of the node in the zero sequence circuit (for instance, if a transformer has grounded neutral, the node from the grounded side should be represented as “shunted”).



	O	S	s0	Тип0	Номер	Название	№ АРМ	U_ном
1				y	1			33
2				y	2			33
3				y	3			33
4				y	4			33

Fig.4.3 – Table of nodes

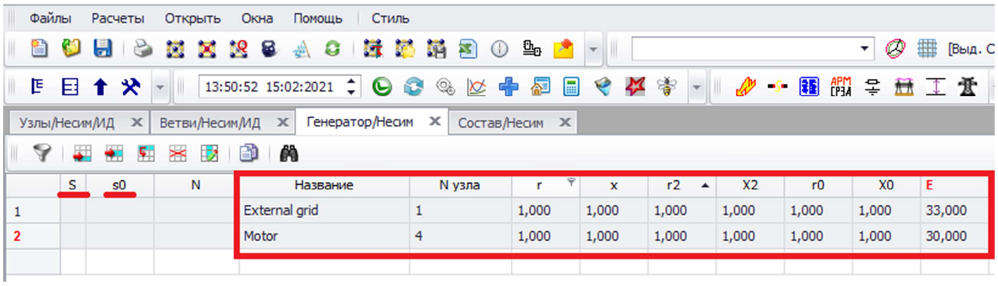
A table of branches should contain each branch from the preliminary circuit and their complex positive, negative and zero sequence impedances, see figure 4.4. Also, there are columns named *S* and *S0*. These columns correspond to the existence of the branch in the positive/negative and zero sequence circuit respectively. For instance, if the power line doesn’t carry the zero sequence current or it is out of service, it is possible to disconnect it from the rest of the network, using these 2 columns.



	O	S	Тип	s0	tip0	N_нач	N_кон	N_п	Название	R	X	G	B	БД_...	N_анц	Кт/г	r0	x0
1			ЛЭП		ЛЭП	1	2		-	1,00	1,00						1,000	1,000
2			ЛЭП		ЛЭП	2	3		-	1,00	10,00						1,000	10,000
3			ЛЭП		ЛЭП	3	4		-	1,00	1,00						1,000	1,000

Fig.4.4 – Table of branches

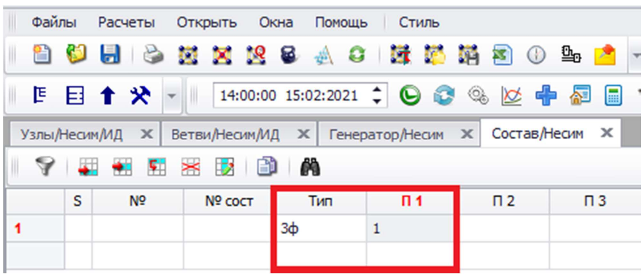
A table of SC current sources carries information about sources of the short-circuit current in the network. Columns of this table should contain a phase-to-phase value of electromotive force and positive, negative and zero sequence impedances of these sources such as external grid, generators and electric motors. Also there are columns named *S* and *S0* which allow disconnecting sources from the network in different sequence circuits, same as in the table of branches, see figure 4.5.



	S	s0	N	Название	N узла	r	x	r2	X2	r0	X0	E
1				External grid	1	1,000	1,000	1,000	1,000	1,000	1,000	33,000
2				Motor	4	1,000	1,000	1,000	1,000	1,000	1,000	30,000

Fig.4.5 – Table of SC current sources

A table of fault locations contains information about the type of the fault (i.e. phase-to-earth, phase-to-phase fault) and the number of the node where the fault occurs, see figure 4.6.



	S	№	№ сост	Тип	П 1	П 2	П 3
1				3ф	1		

Fig.4.6 – Table of the fault locations

When all tables are filled in it's possible to start calculation using the button "calculate" on the instrument panel of the software, figure 4.7. Calculated values will appear in tables of branches and SC current sources in absolute units refereed to the voltage level pointed out in the table of nodes. Then these currents can be recalculated to the actual voltage level of each branch only by hand using formula 2.1 but with reciprocal transformers ratios.

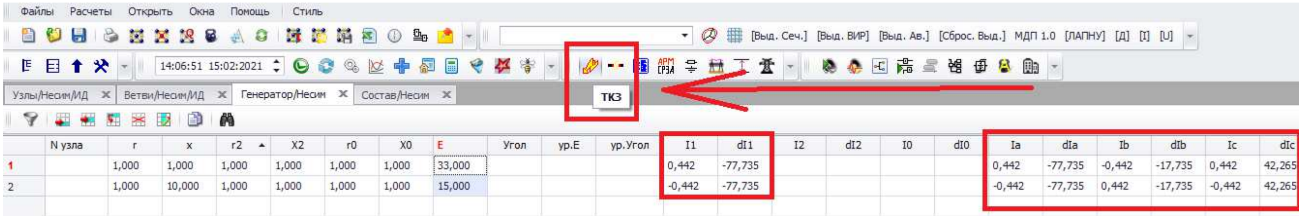


Fig.4.7 – Calculation of the fault currents

4.2.2 Calculation of the short-circuit impedance

RastrKZ has the feature that allows it to calculate short-circuit complex impedance of the network refereed to a certain node. All that is needed is to configure the network's positive, negative and zero sequence circuits correctly, call short-circuit impedance calculator, pick the node number and start calculation using the special button, figure 4.8.

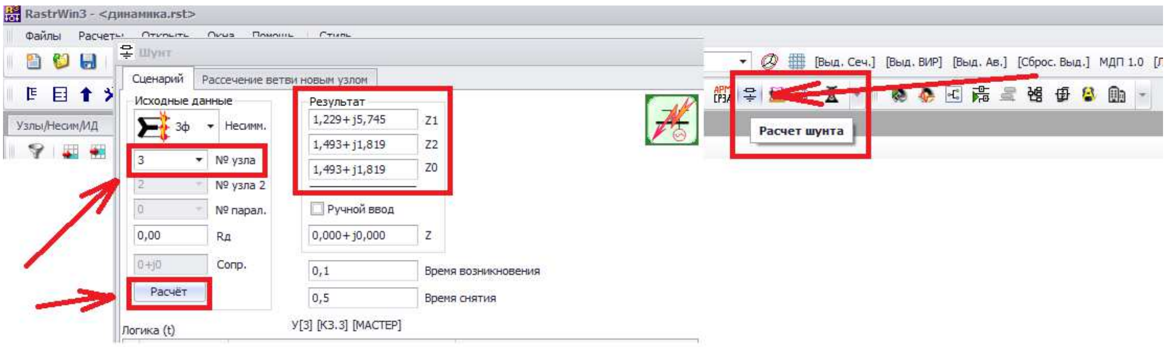


Fig.4.8 – Calculation of the short-circuit impedance

4.3 Limitations of the RastrKZ software

As RastrKZ is a commercial product, it has some limitations. One of them and the most important in terms of this Diploma thesis is the number of nodes limitation. The student version of the RastrKZ allows calculating SC currents in networks with 60 or less nodes only. It affects the dimensions of the network which can be chosen as an object of research.

5. Practical calculations of the symmetrical and peak values of the short-circuit current using RastrKZ software

5.1 Preliminary circuit preparation

According to the limitation which applies to the student version of RastrKZ software, the part of the real industrial network was chosen as an object of the short-circuit current calculations. Input data for all elements included in the studied network was obtained from ABB company's initial reports. The single line diagram of the studied network is depicted in figure 5.1.

As it was shown in chapter 4 of this thesis, to use the RastrKZ software it's required to create preliminary circuits which contain information about positive, negative and zero sequence complex impedances and electromotive forces of the short-circuit current sources calculated in absolute units transformed to the main voltage level (in case of our network, the main voltage level is chosen as 400 kV), also each node should be numbered. A positive sequence preliminary circuit for the studied network is depicted in figure 5.2. A passive load or load without rotating electric machines is not taken into account, because it doesn't contribute to the short-circuit current.

5.2 Preliminary circuit parameters calculation

Calculations of the preliminary circuit's parameters were made in the MathCad 15 software using formulas from chapter 2 of this diploma thesis. Examples of calculation for each type of power system element with references to the formulas from chapter 2 are provided below. Parameters of all elements with reference to the nodes' numbers in figure 5.2 are consolidated in tables 5.1 and 5.2.

5.2.1 External grid's parameters calculation

Given data:	$U_n = 400\,\text{kV}$, $I_{SC}^{(3)} = 9{,}52\,\text{kA}$.
Calculation:	According to the formula 2.14 in clause 2.3.1: $E_S = 400\,\text{kV}$; (Phase-to-phase voltage is required to be inserted into the RastrKZ) $\underline{z}_S^{(1)} = j \cdot x_S = j \cdot \frac{U_n}{\sqrt{3} \cdot I_{SC}^{(3)}} = j \cdot \frac{400}{\sqrt{3} \cdot 9{,}52} = j \cdot 24{,}258\ \Omega$; $\underline{z}_S^{(1)} = \underline{z}_S^{(2)} = \underline{z}_S^{(0)}$.

5.2.2 Overhead line's parameters calculation

Given data:	$U_n = 400\,\text{kV}$, $L_1 = 0{,}9\,\text{km}$, $\text{number of parallel runs} = 1$, $r_{p.u.}^{(1,2)} = 0{,}086628 \frac{\Omega}{\text{km}}$, $x_{p.u.}^{(1,2)} = 0{,}52693 \frac{\Omega}{\text{km}}$, $r_{p.u.}^{(0)} = 0{,}310481 \frac{\Omega}{\text{km}}$, $x_{p.u.}^{(0)} = 1{,}32234 \frac{\Omega}{\text{km}}$.
Calculation:	According to formulas 2.32 and 2.37 in clause 2.3.5: $\underline{z}_1^{(1)} = \underline{z}_1^{(2)} = (r_{p.u.}^{(1,2)} + j \cdot x_{p.u.}^{(1,2)}) \cdot L_1 = 0{,}078 + j \cdot 0{,}474\ \Omega$; $\underline{z}_1^{(0)} = (r_{p.u.}^{(0)} + j \cdot x_{p.u.}^{(0)}) \cdot L_1 = 0{,}279 + j \cdot 1{,}19\ \Omega$;

5.2.3 Cable line's parameters calculation

Given data:	$U_n = 33\text{kV}$, $L_3 = 0{,}5\text{km}$, $\text{number of parallel runs} = 2$, $r_{p.u.}^{(1,2)} = 0{,}07728\dfrac{\Omega}{\text{km}}$, $x_{p.u.}^{(1,2)} = 0{,}1356\dfrac{\Omega}{\text{km}}$, $r_{p.u.}^{(0)} = 0{,}30924\dfrac{\Omega}{\text{km}}$, $x_{p.u.}^{(0)} = 0{,}5428\dfrac{\Omega}{\text{km}}$.
Calculation:	According to formulas 2.55 in clause 2.3.6: $\underline{z}_3^{(1)} = \underline{z}_3^{(2)} = \dfrac{(r_{p.u.}^{(1,2)} + j \cdot x_{p.u.}^{(1,2)}) \cdot L_3}{\text{number of parallel runs}} = 0{,}01932 + j \cdot 0{,}0339\ \Omega$; $\underline{z}_3^{(0)} = \dfrac{(r_{p.u.}^{(0)} + j \cdot x_{p.u.}^{(0)}) \cdot L_3}{\text{number of parallel runs}} = 0{,}07731 + j \cdot 0{,}1357\ \Omega$; As the nominal voltage of the cable is 33 kV, its complex impedances should be transformed to the 400 kV voltage level using formula 2.1: $\underline{z}_3^{(1)} = \underline{z}_3^{(2)} = (0{,}01932 + j \cdot 0{,}0339) \cdot \left(\dfrac{400}{33}\right)^2 = 2{,}838 + j \cdot 4{,}98\ \Omega$; $\underline{z}_3^{(0)} = (0{,}07731 + j \cdot 0{,}1357) \cdot \left(\dfrac{400}{33}\right)^2 = 11{,}358 + j \cdot 19{,}937\,\Omega$;

5.2.4 Transformer's parameters calculation

Given data:	$U_{n.HV} = 400\text{kV}$, $U_{n.LV} = 33\text{kV}$, $u_k = 12{,}5\%$, $S_n = 200\text{MVA}$.
Calculation:	According to formulas 2.57 and 2.9: $\underline{z}_{TR1}^{(1)} = \underline{z}_{TR1}^{(2)} = \underline{z}_{TR1}^{(0)} = \dfrac{u_k \cdot U_{n.HV}^2}{100 \cdot S_n} = \dfrac{12{,}5 \cdot 400^2}{100 \cdot 200} = j \cdot 100\ \Omega.$ As the nominal voltage of the transformer's primary side is 400 kV and it was used to calculate the transformer's complex impedance, this impedance is automatically transformed to that voltage level and there is no need for other transformations.

5.2.5 Calculation of the 0,4 kV asynchronous motor's parameters

Given data:	$U_n = 0{,}4\text{kV}$, $P_n = 479\text{kW}$, $\cos\varphi = 0{,}82$
Calculation:	Nominal current of the motor: $I_n = \dfrac{P_n}{\sqrt{3} \cdot U_n \cdot \cos\varphi} = \dfrac{479}{\sqrt{3} \cdot 0{,}4 \cdot 0{,}82} = 843{,}142\,\text{A}.$ According to formula 2.28 in clause 2.3.3: $x''_{*AM} = 0{,}18$, $r_{AM} = 0{,}36 \cdot x''_{AM}$, $\underline{z}_{m1}^{(1,2)} = (0{,}18 \cdot 0{,}36 + j \cdot 0{,}18) = 0{,}0648 + j \cdot 0{,}18.$ As the motor's winding is not connected to the ground, there is no path for the zero sequence current to flow through during the ground fault at the motor's terminals. The zero sequence complex impedance for such faults can be assumed to be an infinite value. Faults inside the motor's winding are not considered in this diploma thesis.

	The obtained value is in relative units refereed to the motor's nominal voltage. This value should be converted into the absolute units using formula 2.1: $\underline{z}_{m1}^{(1,2)} = (0,0648 + j \cdot 0,18) \cdot \frac{U_n^2 \cdot \cos\varphi}{P_n} = 0,017748 + j \cdot 0,049302\ \Omega$. Electromotive force of the asynchronous motor according to the formula 2.22: $E_{m1} = \sqrt{(U_n \cdot \cos\varphi - I_n \cdot r_{m1})^2 + (U_n \cdot \sin\varphi - I_n \cdot x_{m1})^2} =$ $= \sqrt{(\frac{400}{\sqrt{3}} \cdot 0,82 - 843,142 \cdot 0,017748)^2 + (\frac{400}{\sqrt{3}} \cdot 0,572 - 843,142 \cdot 0,049302)^2} = 196,54\,\mathrm{V}$. As the nominal voltage of the motor is 0,4 kV, its complex impedances and electromotive force should be transformed to the 400 kV voltage level using formula 2.1: $\underline{z}_{m1}^{(1,2)} = (0,017748 + j \cdot 0,049302) \cdot \left(\frac{400}{0,4}\right)^2 = 17748,98 + j \cdot 49302,72\ \Omega$, $E_{m1} = 196,54 \cdot \left(\frac{400}{0,4}\right) = 196,54\,\mathrm{kV}$. The phase-to-phase value of the electromotive force inserted into the RastrKZ software: $E_{m1} = 196,54 \cdot \sqrt{3} = 340,417$ kV. The resistance of the motor's stator which is used in the calculation of the peak short-circuit current is equal to the motor's resistance due to the lack of any additional data.

5.2.6 Calculation of the 6,6 kV asynchronous motor's parameters

Given data:	$U_n = 6,6\,\mathrm{kV}$, $P_n = 450\,\mathrm{kW}$, $I_n = 50,2\,\mathrm{A}$, $\cos\varphi = 0,83$, $s_n = 1,1\%$, $\underset{*}{I_L} = 6$.
Calculation:	According to formula 2.29 in clause 2.3.3: $x''_{AM} = \frac{1}{\underset{*}{I_L}} \cdot \frac{U_n^2 \cdot \cos\varphi}{P_n} = \frac{1}{6} \cdot \frac{6,6^2 \cdot 0,83}{0,45} = 13,391\Omega$, For calculation of the initial symmetrical short-circuit current the GOST states for motors with the rated voltage above 1 kV to consider only the subtransient reactance, so: $\underline{z}_{m10}^{(1,2)} = j \cdot x''_{AM} = j \cdot 13,391\ \Omega$. As the motor's winding is not connected to the ground, there is no path for the zero sequence current to flow through during the ground fault at the motor's terminals. The zero sequence complex impedance for such faults can be assumed to be an infinite value. Faults inside the motor's winding are not considered in this diploma thesis. Electromotive force of the asynchronous motor according to the formula 2.23: $E_{m10} = \sqrt{(U_n - I_n \cdot x_{m1} \cdot \sin\varphi)^2 + (I_n \cdot x_{m1} \cdot \cos\varphi)^2} =$ $= \sqrt{(\frac{6600}{\sqrt{3}} - 50,2 \cdot 13,391 \cdot 0,5577)^2 + (50,2 \cdot 13,391 \cdot 0,83)^2} = 4222,35\,\mathrm{V}$.

	As the nominal voltage of the motor is 6,6 kV, its complex impedance and electromotive force should be transformed to the 400 kV voltage level using formula 2.1: $\underline{z}_{m10}^{(1,2)} = j \cdot 13,391 \cdot \left(\frac{400}{6,6}\right)^2 = j \cdot 49185,185\ \Omega,$ $E_{m10} = 4222,35 \cdot \left(\frac{400}{6,6}\right) = 255,9\,\text{kV}.$ The phase-to-phase value of the electromotive force inserted into the RastrKZ software: $E_{m10} = 255,9 \cdot \sqrt{3} = 443,231\ \text{kV}.$ The resistance of the motor's stator which is used in the calculation of the peak short-circuit current according to the formula 2.30 transformed to the 400 kV voltage level: $r_1 = \frac{s_n}{100} \cdot \frac{U_n^2 \cdot \cos\varphi}{P_n} \cdot \left(\frac{400}{6,6}\right)^2 = \frac{1,1}{100} \cdot \frac{6,6^2 \cdot 0,83}{0,45} \cdot \left(\frac{400}{6,6}\right)^2 = 3246,222\ \Omega.$

5.2.7 Synchronous generator parameters calculation

Given data:	$U_n = 0,4\,\text{kV}$, $S_n = 1056\,\text{kVA}$, $I_n = 1356\,\text{A}$, $\cos\varphi = 0,8$, $r_{g1} = 2,03 \cdot 10^{-3}\ \Omega$, $x_d^{''} = 0,16.$
Calculation:	Generator's resistance in absolute units: $r_{g1}^{(1,2,0)} = 0,00203\ \Omega,$ Generator's reactance value is in relative units refereed to its nominal voltage. This value should be converted into the absolute units using formula 2.1: $x_{g1}^{(1,2,0)} = x_d^{''} \cdot \frac{U_n^2}{S_n} = 0,16 \cdot \frac{0,4^2}{1,056} = 0,0242\ \Omega,$ Generator's complex impedance: $\underline{z}_{g1}^{(1,2,0)} = r_{g1}^{(1,2,0)} + j \cdot x_{g1}^{(1,2,0)} = 0,00203 + j \cdot 0,0242\ \Omega.$ Electromotive force of generator according to the formula 2.15: $E_{g1} = \sqrt{(U_n + I_n \cdot x_{g1} \cdot \sin\varphi)^2 + (I_n \cdot x_{g1} \cdot \cos\varphi)^2} =$ $= \sqrt{(\frac{400}{\sqrt{3}} + 1356 \cdot 0,0242 \cdot 0,6)^2 + (1356 \cdot 0,0242 \cdot 0,8)^2} = 252,039\,\text{V}.$ As the nominal voltage of the generator is 0,4 kV, its complex impedances and electromotive force should be transformed to the 400 kV voltage level using formula 2.1: $\underline{z}_{g1}^{(1,2,0)} = (0,00203 + j \cdot 0,0242) \cdot \left(\frac{400}{0,4}\right)^2 = 2030 + j \cdot 24242,42\ \Omega,$ $E_{g1} = 252,039 \cdot \left(\frac{400}{0,4}\right) = 252,039\,\text{kV}.$ The phase-to-phase value of the electromotive force inserted into the RastrKZ software: $E_{g1} = 252,039 \cdot \sqrt{3} = 436,544\ \text{kV}.$

5.2.8 Overview of the calculated parameters for the preliminary circuit

All elements in the preliminary circuit can be divided into two groups:

1) Sources of the short-circuit current (i.e. external grid, synchronous generators, motors);

2) Power system elements which link sources of the short-circuit current (i.e. overhead lines, cable lines, power transformers).

Calculated parameters, used in positive, negative and zero sequence preliminary circuits, for the first group are collected in table 5.1, for the second group in table 5.2.

Table 5.1 – Short-circuit current sources parameters

Name of the source	Node number	$\underline{z}^{(1,2)}$, Ω	$\underline{z}^{(0)}$, Ω	E, kV
External grid	1	$j \cdot 24{,}258$	$j \cdot 24{,}258$	400
Generator 1	36	$2030 + j \cdot 24242{,}42$	$2030 + j \cdot 24242{,}42$	436,544
Generator 2	33	$2030 + j \cdot 24242{,}42$	$2030 + j \cdot 24242{,}42$	436,544
Motor 1	10	$17748{,}98 + j \cdot 49302{,}72$	-	340,417
Motor 2	13	$10561{,}1 + j \cdot 29336{,}6$	-	340,417
Motor 3	36	$38820{,}8 + j \cdot 107835{,}6$	-	340,417
Motor 4	36	$38820{,}8 + j \cdot 107835{,}6$	-	340,417
Motor 5	18	$j \cdot 77066{,}95$	-	441,846
Motor 6	19	$j \cdot 77066{,}95$	-	441,846
Motor 7	20	$j \cdot 77066{,}95$	-	441,846
Motor 8	21	$j \cdot 77066{,}95$	-	441,846
Motor 9	22	$j \cdot 77066{,}95$	-	441,846
Motor 10	40	$j \cdot 49185{,}19$	-	443,231
Motor 11	41	$j \cdot 40000$	-	442,019
Motor 12	42	$j \cdot 40000$	-	442,019
Motor 13	43	$j \cdot 44270$	-	443,058
Motor 14	26	$9092{,}79 + j \cdot 25257{,}7$	-	340,417
Motor 15	33	$13989{,}1 + j \cdot 38842{,}1$	-	340,417
Motor 16	33	$13989{,}1 + j \cdot 38842{,}1$	-	340,417

Table 5.2 - Power transformers` and overhead and cable lines` parameters

Name of the element	Starting-ending nodes	$\underline{z}^{(1,2)}$, Ω	$\underline{z}^{(0)}$, Ω
OHL 1	1-2	$0{,}078 + j \cdot 0{,}474$	$0{,}279 + j \cdot 1{,}19$
OHL 2	1-3	$0{,}078 + j \cdot 0{,}474$	$0{,}279 + j \cdot 1{,}19$
CL 3	4-6	$2{,}838 + j \cdot 4{,}98$	$11{,}358 + j \cdot 19{,}937$
CL 4	5-7	$2{,}838 + j \cdot 4{,}98$	$11{,}358 + j \cdot 19{,}937$
CL 5	6-8	$0{,}94 + j \cdot 0{,}92$	$3{,}762 + j \cdot 3{,}692$
CL 6	9-10	$751{,}25 + j \cdot 1256{,}64$	$3005 + j \cdot 5026{,}55$
CL 7	6-11	$0{,}94 + j \cdot 0{,}92$	$3{,}762 + j \cdot 3{,}692$

Continuation of table 5.2

Name of the element	Starting-ending nodes	$\underline{z}^{(1,2)}$, Ω	$\underline{z}^{(0)}$, Ω
CL 8	12-13	$751{,}25+j\cdot 1256{,}64$	$3005+j\cdot 5026{,}55$
CL 9	6-14	$0{,}157+j\cdot 0{,}277$	$0{,}631+j\cdot 1{,}108$
CL 10	15-16	$2{,}993+j\cdot 4{,}615$	$11{,}975+j\cdot 18{,}463$
CL 11	7-27	$0{,}157+j\cdot 0{,}277$	$0{,}631+j\cdot 1{,}108$
CL 12	28-29	$2{,}993+j\cdot 4{,}615$	$11{,}975+j\cdot 18{,}463$
CL 13	7-34	$0{,}94+j\cdot 0{,}92$	$3{,}762+j\cdot 3{,}692$
CL 14	35-36	$751{,}25+j\cdot 1256{,}64$	$3005+j\cdot 5026{,}55$
CL 16	16-18	$136{,}64+j\cdot 100{,}29$	$546{,}556+j\cdot 401{,}154$
CL 17	16-19	$132{,}09+j\cdot 96{,}95$	$528{,}338+j\cdot 387{,}782$
CL 18	16-20	$127{,}53+j\cdot 93{,}6$	$510{,}119+j\cdot 374{,}410$
CL 19	16-21	$122{,}98+j\cdot 90{,}26$	$491{,}9+j\cdot 361{,}039$
CL 20	16-22	$118{,}42+j\cdot 86{,}92$	$473{,}682+j\cdot 347{,}667$
CL 21	16-23	$265{,}592+j\cdot 193{,}169$	$1062{,}711+j\cdot 772{,}676$
CL 22	23-24	$28{,}558+j\cdot 20{,}77$	$114{,}27+j\cdot 83{,}083$
CL 23	25-26	$1001{,}67+j\cdot 1675{,}52$	$4006{,}67+j\cdot 6702{,}07$
CL 24	29-30	$265{,}592+j\cdot 193{,}169$	$1062{,}711+j\cdot 772{,}676$
CL 25	30-31	$28{,}558+j\cdot 20{,}77$	$114{,}27+j\cdot 83{,}083$
CL 26	32-33	$1001{,}67+j\cdot 1675{,}52$	$4006{,}67+j\cdot 6702{,}07$
CL 30	29-40	$182{,}19+j\cdot 133{,}72$	$728{,}742+j\cdot 534{,}872$
CL 31	29-41	$91{,}092+j\cdot 66{,}86$	$364{,}371+j\cdot 267{,}436$
CL 32	29-42	$104{,}76+j\cdot 76{,}89$	$419{,}027+j\cdot 307{,}552$
CL 33	29-43	$118{,}42+j\cdot 86{,}92$	$473{,}682+j\cdot 347{,}667$
TR 1	2-4	$j\cdot 100$	$j\cdot 100$
TR 2	3-5	$j\cdot 100$	$j\cdot 100$
TR 3	8-9	$j\cdot 6000$	$j\cdot 6000$
TR 4	11-12	$j\cdot 6000$	$j\cdot 6000$
TR 5	14-15	$j\cdot 640$	$j\cdot 640$
TR 6	27-28	$j\cdot 640$	$j\cdot 640$
TR 7	34-35	$j\cdot 6000$	$j\cdot 6000$
TR 8	24-25	$j\cdot 6400$	$j\cdot 6400$
TR 9	31-32	$j\cdot 6400$	$j\cdot 6400$

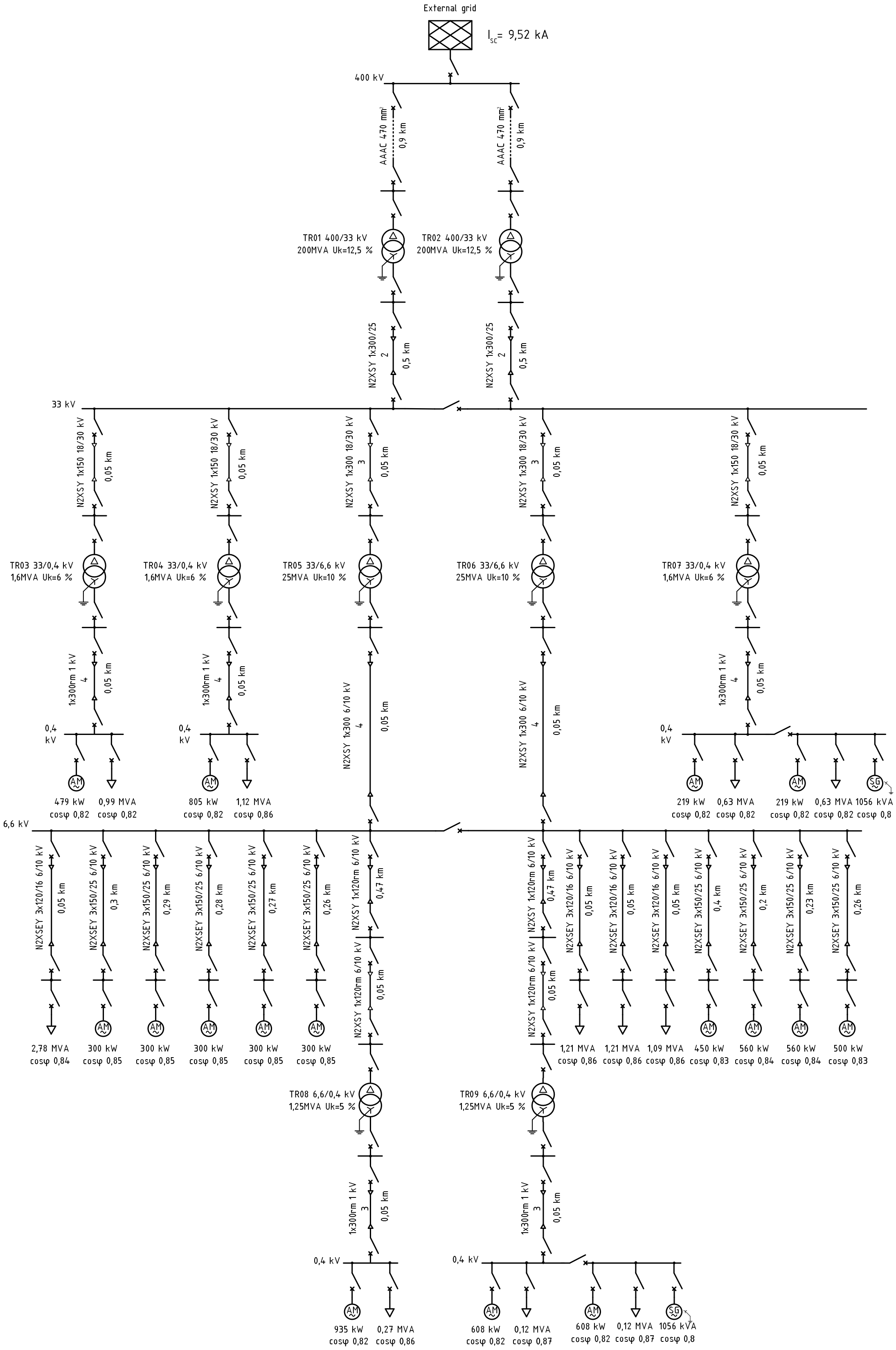


Fig.5.1 – Single line diagram of the network

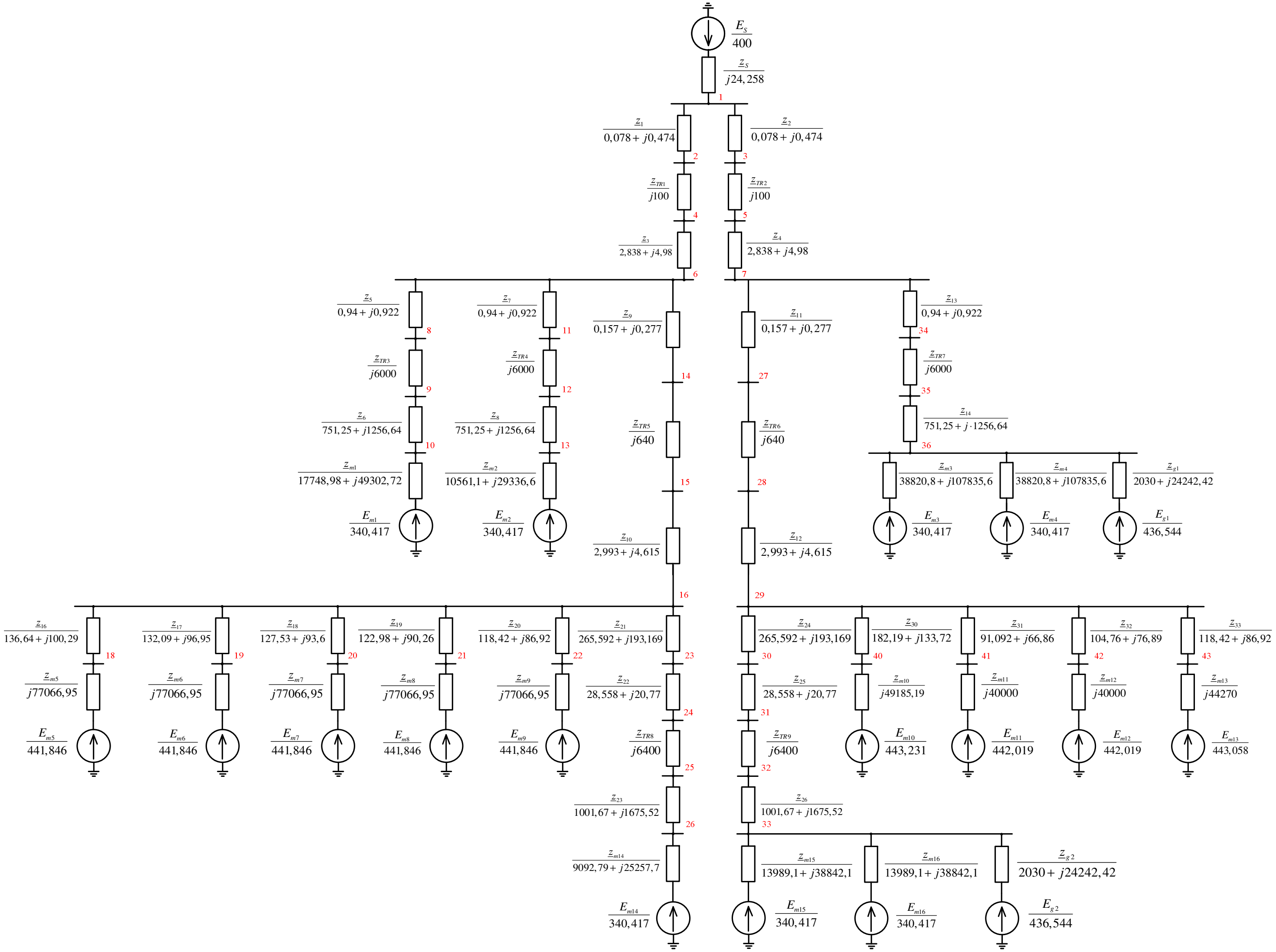


Fig.5.2 – Positive sequence preliminary circuit

5.3 Calculation of the symmetrical component of the short-circuit current

Three-phase and phase-to-earth fault's symmetrical component of the short-circuit current was calculated using RastrKZ software. Ten places of fault with the range of voltages from 0,4 kV up to 400 kV were chosen.

The RastrKZ is capable to calculate the short-circuit current refereed to the main voltage level (in our case it's 400 kV), therefore the values of the symmetrical short-circuit currents at places of faults where the rated voltage is not 400 kV should be transformed to their rated levels using formula 2.1 and reciprocal transformer ratios. An example of such transformation for the three-phase fault in node 6 can be seen below:

Given data:	$I_{S0} = 1{,}8101\text{kA}$ - refereed to 400 kV $U_{main} = 400\text{kV}$, $U_{n.fault} = 33\text{kV}$.
Calculation:	Transformation of the symmetrical short-circuit current to the fault's rated voltage: $I_{S0} = 1{,}8101 \cdot \frac{U_{main}}{U_{n.fault}} = 1{,}8101 \cdot \frac{400}{33} = 21{,}941\text{kA}.$

Calculated symmetrical short-circuit currents for three-phase faults are collected in table 5.3. Symmetrical short-circuit currents for the phase-to-earth faults are collected in table 5.4.

Table 5.3 – Symmetrical short-circuit currents for three-phase faults

Location of the fault (node's number)	I_{S0},kA refereed to 400 kV	Rated voltage of the fault location, kV	I_{S0},kA refereed to the rated voltage of the place of fault
1	9,5883	400	9,588
6	1,8101	33	21,941
7	1,8218	33	22,082
10	0,0348	0,4	34,8
13	0,0373	0,4	37,3
36	0,0448	0,4	44,8
16	0,3197	6,6	19,376
29	0,3326	6,6	20,158
26	0,0326	0,4	32,6
33	0,0452	0,4	45,2

Table 5.4 – Symmetrical short-circuit currents for phase-to-earth faults

Location of the fault (node's number)	I_{S0},kA refereed to 400 kV	Rated voltage of the fault location, kV	I_{S0},kA refereed to the rated voltage of the place of fault
1	9,5658	400	9,566
6	1,845	33	22,364
7	1,845	33	22,364
10	0,0279	0,4	27,900
13	0,0288	0,4	28,800
36	0,0384	0,4	38,400

Continuation of table 5.4

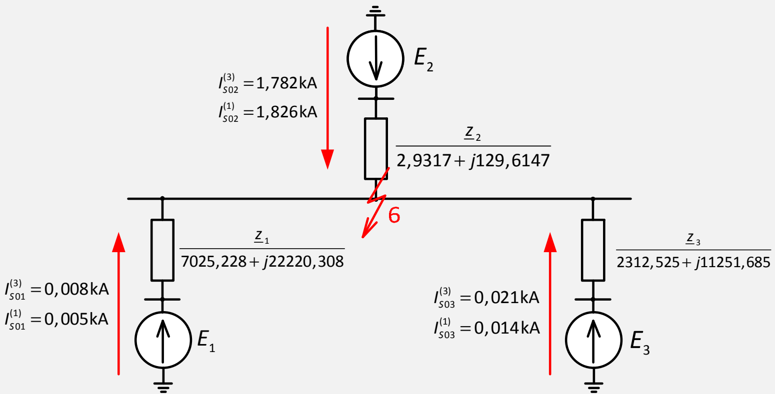
Location of the fault (node's number)	I_{S0},kA refereed to 400 kV	Rated voltage of the fault location, kV	I_{S0},kA refereed to the rated voltage of the place of fault
16	0,3294	6,6	19,964
29	0,339	6,6	20,545
26	0,0246	0,4	24,600
33	0,0363	0,4	36,300

5.4 Peak value of the short-circuit current calculation

RastrKZ is not capable of calculating the peak value of the short-circuit current automatically, so it was performed by hand using MathCad15 software and RastrKZ's feature, described in clause 4.2.2, which allows calculating short-circuit impedance.

As the studied network at each place of the fault can be divided into a certain number of branches which contribute to the peak value of the short-circuit current independently, the peak value of the short-circuit current can be calculated using the superposition method according to formula 3.18.

An example of such calculation for three-phase and phase-to-earth faults in node 6 can be seen below:

Data, obtained from the RastrKZ software:	$\underline{Z}_1 = 7025{,}228 + j \cdot 22220{,}308\ \Omega,\ I_{S01}^{(3)} = 0{,}008\,\text{kA}, I_{S01}^{(1)} = 0{,}005\,\text{kA},$ $\underline{Z}_2 = 2{,}9137 + j \cdot 129{,}6147\ \Omega,\ I_{S02}^{(3)} = 1{,}782\,\text{kA}, I_{S02}^{(1)} = 1{,}826\,\text{kA},$ $\underline{Z}_3 = 2312{,}525 + j \cdot 11251{,}685\ \Omega,\ I_{S03}^{(3)} = 0{,}021\,\text{kA}, I_{S03}^{(1)} = 0{,}014\,\text{kA}.$ $U_{main} = 400\,\text{kV},\ U_{n.fault} = 33\,\text{kV}$
Calculation:	According to the superposition method the whole network is simplified to 3 independent branches around the node, where the fault occurs. Each branch contributes by some amount of peak current to the total peak current in node 6. The network simplified around node 6 is depicted in figure 5.3.  Fig.5.3 – Simplified network According to formula 3.9 time constants of the aperiodic short-circuit current component decay from each branch:

$$T_{a1} = \frac{\mathrm{Im}(\underline{z}_1)}{w_c \cdot \mathrm{Re}(\underline{z}_1)} = \frac{22220{,}308}{2 \cdot \pi \cdot 50 \cdot 7025} = 0{,}0101 \text{ s},$$

$$T_{a2} = \frac{\mathrm{Im}(\underline{z}_2)}{w_c \cdot \mathrm{Re}(\underline{z}_2)} = \frac{129{,}6147}{2 \cdot \pi \cdot 50 \cdot 2{,}9317} = 0{,}1407 \text{ s},$$

$$T_{a3} = \frac{\mathrm{Im}(\underline{z}_3)}{w_c \cdot \mathrm{Re}(\underline{z}_3)} = \frac{11251{,}685}{2 \cdot \pi \cdot 50 \cdot 2312{,}525} = 0{,}0155 \text{ s}.$$

Peak coefficients according to formula 3.15 for each branch :

$$K_{p1} = 1{,}02 + 0{,}98 \cdot e^{\frac{-3}{w_c \cdot T_{a1}}} = 1{,}02 + 0{,}98 \cdot e^{\frac{-3}{2 \cdot \pi \cdot 50 \cdot 0{,}0101}} = 1{,}3996,$$

$$K_{p2} = 1{,}02 + 0{,}98 \cdot e^{\frac{-3}{w_c \cdot T_{a2}}} = 1{,}02 + 0{,}98 \cdot e^{\frac{-3}{2 \cdot \pi \cdot 50 \cdot 0{,}1407}} = 1{,}9357,$$

$$K_{p3} = 1{,}02 + 0{,}98 \cdot e^{\frac{-3}{w_c \cdot T_{a3}}} = 1{,}02 + 0{,}98 \cdot e^{\frac{-3}{2 \cdot \pi \cdot 50 \cdot 0{,}0155}} = 1{,}549.$$

According to formula 3.18, the peak value of the three-phase short-circuit current in node 6:

$$i_p^{(3)} = \sqrt{2} \cdot (I_{S01}^{(3)} \cdot K_{p1} + I_{S02}^{(3)} \cdot K_{p2} + I_{S03}^{(3)} \cdot K_{p3}) =$$
$$= \sqrt{2} \cdot (0{,}008 \cdot 1{,}3996 + 1{,}782 \cdot 1{,}9357 + 0{,}021 \cdot 1{,}549) = 4{,}9401 \text{kA}.$$

The peak value of the phase-to-earth short-circuit current in node 6:

$$i_p^{(1)} = \sqrt{2} \cdot (I_{S01}^{(1)} \cdot K_{p1} + I_{S02}^{(1)} \cdot K_{p2} + I_{S03}^{(1)} \cdot K_{p3}) =$$
$$= \sqrt{2} \cdot (0{,}005 \cdot 1{,}3996 + 1{,}826 \cdot 1{,}9357 + 0{,}014 \cdot 1{,}549) = 5{,}0392 \text{kA}.$$

Transformation of the peak currents to the fault's rated voltage:

$$i_p^{(3)} = 4{,}9401 \cdot \frac{U_{main}}{U_{n.fault}} = 4{,}9401 \cdot \frac{400}{33} = 59{,}88 \text{kA},$$

$$i_p^{(1)} = 5{,}0392 \cdot \frac{U_{main}}{U_{n.fault}} = 5{,}0392 \cdot \frac{400}{33} = 61{,}081 \text{kA}.$$

Calculated peak values of the short-circuit current for three-phase faults are collected in table 5.5. Peak values of the short-circuit current for phase-to-earth faults are collected in table 5.6.

Table 5.5 –Peak values of the short-circuit current for the three-phase faults

Location of the fault (node's number)	$i_p^{(3)}$,kA refereed to 400 kV	Rated voltage of the fault location, kV	$i_p^{(3)}$,kA refereed to the rated voltage of the place of fault
1	27,081	400	27,081
6	4,940	33	59,880
7	4,972	33	60,261
10	0,084	0,4	84,000
13	0,088	0,4	88,100
36	0,109	0,4	108,700
16	0,882	6,6	53,467
29	0,918	6,6	55,648

Continuation of table 5.5

Location of the fault (node's number)	$i_p^{(3)}$,kA refereed to 400 kV	Rated voltage of the fault location, kV	$i_p^{(3)}$,kA refereed to the rated voltage of the place of fault
26	0,073	0,4	73,400
33	0,102	0,4	102,400

Table 5.6 –Peak values of the short-circuit current for the phase-to-earth faults

Location of the fault (node's number)	$i_p^{(1)}$,kA refereed to 400 kV	Rated voltage of the fault location, kV	$i_p^{(1)}$,kA refereed to the rated voltage of the place of fault
1	27,030	400	27,030
6	5,039	33	61,081
7	5,065	33	61,393
10	0,068	0,4	67,800
13	0,069	0,4	69,400
36	0,093	0,4	92,500
16	0,912	6,6	55,291
29	0,939	6,6	56,915
26	0,056	0,4	56,200
33	0,082	0,4	82,200

6. Comparison of results of the short-circuit current calculation using GOST and IEC methods

6.1 Results of calculation according to the IEC and GOST standards

To calculate the symmetrical and peak values of the short-circuit current in the same network using IEC 60909, DigSilent2018 software was chosen. The same input data was inserted into the software and required values were calculated.

Values of the symmetrical short-circuit current and peak values of the short-circuit current calculated according to the IEC 60909 and GOST standards for three-phase short-circuit faults are collected in table 6.1.

Table 6.1 – Symmetrical and peak values of three-phase short-circuit faults, calculated according to the IEC 60909 and GOST standards

Location of the fault (node's number)	Voltage level, kV	IEC 60909		GOST		ΔI_{S0},%	$\Delta i_p^{(3)}$,%
		I_{S0},kA	$i_p^{(3)}$,kA	I_{S0},kA	$i_p^{(3)}$,kA		
1	400	9,590	27,100	9,588	27,081	0,018	0,070
6	33	24,190	66,200	21,941	59,880	9,299	9,547
7	33	24,300	66,380	22,082	60,261	9,126	9,219
10	0,4	38,140	93,610	34,8	84,000	8,757	10,266
13	0,4	41,180	101,120	37,3	88,100	9,422	12,876
36	0,4	47,150	114,720	44,8	108,700	4,984	5,248
16	6,6	21,430	59,450	19,376	53,467	9,586	10,064
29	6,6	22,110	61,010	20,158	55,648	8,831	8,788
26	0,4	34,050	78,340	32,6	73,400	4,258	6,306
33	0,4	48,370	114,490	45,2	102,400	6,554	10,560

Values of the symmetrical short-circuit current and peak values of the short-circuit current calculated according to the IEC 60909 and GOST standards for phase-to-earth short-circuit faults are collected in table 6.2.

Table 6.2 – Symmetrical and peak values of phase-to-earth short-circuit faults, calculated according to the IEC 60909 and GOST standards

Location of the fault (node's number)	Voltage level, kV	IEC 60909		GOST		ΔI_{S0},%	$\Delta i_p^{(1)}$,%
		I_{S0},kA	$i_p^{(1)}$,kA	I_{S0},kA	$i_p^{(1)}$,kA		
1	400	9,570	27,030	9,566	27,030	0,044	0,002
6	33	24,830	67,860	22,364	61,081	9,933	9,989
7	33	24,910	68,020	22,364	61,393	10,222	9,743
10	0,4	30,510	74,880	27,900	67,800	8,555	9,455
13	0,4	31,750	77,970	28,800	69,400	9,291	10,991
36	0,4	40,510	98,570	38,400	92,500	5,209	6,158
16	6,6	22,140	61,410	19,964	55,291	9,830	9,964
29	6,6	22,620	62,410	20,545	56,915	9,171	8,804
26	0,4	26,280	60,460	24,600	56,200	6,393	7,046
33	0,4	38,940	92,190	36,300	82,200	6,780	10,836

6.2 Description of the differences in results and their reasons

The difference between values of the short-circuit currents calculated according to the GOST and IEC standards can be seen in tables 6.1 and 6.2. Values calculated according to the IEC 60909 are higher than ones calculated according to the GOST and in some cases the difference can reach 13 %. This difference can be caused by 3 main reasons:

1) Using c-factor in calculations according to the IEC 60909;

2) Difference in the models of the power system elements;

3) Inaccuracy in calculations.

If we compare the general form of the formula 3.2 used for calculation of the short-circuit currents with the formulas 29 and 52 from IEC 60909-0, we can note that formulas 29 and 52 have a multiplier which formula 3.2 doesn't have – c-factor. The c-factor is chosen from table 1 in IEC 60909-0 according to the voltage level of the place of fault. In this diploma thesis, maximum short-circuit currents were calculated, so maximum c-factor values were used (which are typically 1,05 or 1,1), therefore results of calculation according to the IEC are higher than ones calculated according to GOST.

The c-factor has influence not only in the numerator of the formulas 29 and 52, [5] but also in the denominator because it is included in the calculation of the complex impedance of some power system elements such as network feeders (formulas 4 and 5, [5]), transformers (formulas 7 and 12a, [5]) and synchronous generators (formulas 17 and 18, [5]). Let's calculate complex impedances of the above-mentioned power system elements and compare these values with values which were calculated in chapter 5 according to the GOST standard.

Network feeder

Given data:	$U_n = 400\,\text{kV}$, $I_{SC}^{(3)} = 9{,}52\,\text{kA}$, c = 1,1.
Calculation:	According to formulas 4 and 5, IEC 60909-0: $\underline{z}_S^{(1)} = j \cdot x_S = j \cdot \frac{c \cdot U_n}{\sqrt{3} \cdot I_{SC}^{(3)}} = j \cdot \frac{1{,}1 \cdot 400}{\sqrt{3} \cdot 9{,}52} = j \cdot 26{,}684\ \Omega$, $\underline{z}_S^{(1)} = \underline{z}_S^{(2)} = \underline{z}_S^{(0)}$.
GOST:	$E_S = 400\,\text{kV}$, $\underline{z}_S^{(1)} = j \cdot 24{,}258\ \Omega$, $\underline{z}_S^{(1)} = \underline{z}_S^{(2)} = \underline{z}_S^{(0)}$.
Conclusion:	In case of calculation of the short-circuit current at the busbar of the feeder using formulas 29 and 52, it is seen that c-factors will cancel each other, so the difference between GOST and IEC, in this case, is negligible (can be proven by the difference of the short-circuit currents calculated in the node 1 according to the GOST and IEC, which is lower than 0,1 %). In other cases, increase in the complex impedance of the feeder will lead to decrease in the short-circuit current which can feeder supply to the place of fault.

Transformer

Given data:	$U_{n.HV}=400\text{kV}$, $U_{n.LV}=33\text{kV}$, $u_k=12{,}5\%$, $S_n=200\text{MVA}$.
Calculation:	According to formulas 7 and 12a, IEC 60909-0: $\underline{z}_{TR1}^{(1)}=\underline{z}_{TR1}^{(2)}=\underline{z}_{TR1}^{(0)}=K_T\cdot\frac{u_k\cdot U_{n.HV}^2}{100\cdot S_n}=0{,}95\cdot\frac{c}{1+\frac{0{,}6\cdot u_k}{100}}\cdot\frac{u_k\cdot U_{n.HV}^2}{100\cdot S_n}=$ $=0{,}95\cdot\frac{c}{1+\frac{0{,}6\cdot 12{,}5}{100}}\frac{12{,}5\cdot 400^2}{100\cdot 200}=j\cdot 97{,}209\ \Omega.$
GOST:	$\underline{z}_{TR1}^{(1)}=\underline{z}_{TR1}^{(2)}=\underline{z}_{TR1}^{(0)}=j\cdot 100\ \Omega.$
Conclusion:	It\`s seen that the complex impedance of the transformer according to the IEC 60909-0 is lower than according to the GOST. This fact leads to the decrease in the short-circuit impedance of the whole network and therefore to increase in the short-circuit current.

Synchronous generator

Given data:	$U_n=0{,}4\text{kV}$, $S_n=1056\text{kW}$, $I_n=1356\text{A}$, $\cos\varphi=0{,}8$, $r_{g1}=2{,}03\cdot 10^{-3}\ \Omega$, $x_d''=0{,}16$.
Calculation:	Generator's resistance in absolute units: $r_{g1}^{(1,2,0)}=0{,}00203\ \Omega,$ Generator's reactance value in absolute units : $x_{g1}^{(1,2,0)}=x_d''\cdot\frac{U_n^2}{S_n}=0{,}16\cdot\frac{0{,}4^2}{1{,}056}=0{,}0242\ \Omega,$ Correction factor, according to formula 18, IEC 60909-0: $K_g=\frac{U_n}{U_{rG}}\cdot\frac{c_{\max}}{1+x_d''\cdot\sin\varphi}=\frac{0{,}4}{0{,}4}\cdot\frac{1{,}05}{1+0{,}16\cdot 0{,}6}=0{,}958,$ Complex impedance of the generator: $\underline{z}_{g1}^{(1,2,0)}=K_g\cdot(0{,}00203+j\cdot 0{,}0242)=0{,}001944+j\cdot 0{,}02322\ \Omega.$
GOST:	$\underline{z}_{g1}^{(1,2,0)}=0{,}00203+j\cdot 0{,}0242\ \Omega$, $E_{g1}=252{,}039\text{V}$.
Conclusion:	It\`s seen that the complex impedance of the generator according to the IEC 60909-0 is lower than according to the GOST. This fact leads to the decrease in the short-circuit impedance of the whole network and therefore to increase in the short-circuit current, which can generator supply to the place of fault.

As the studied network is meshed, it\`s a very complex problem to derive the dependence of the short-circuit impedance on c-factors of different elements in the network in symbolic form, but using DigSilent software we can calculate short-circuit currents assuming c-factors equal to one, to assess their influence on results. Comparison between results calculated using proper values of c-factors and c-factors are equal to one is in table 6.3 and table 6.4.

Table 6.3 – Influence of c-factors on the results of the three-phase short-circuit current calculations according to the IEC 60909

Location of the fault (node's number)	Voltage level, kV	IEC 60909		IEC 60909 (c-factor = 1)		ΔI_{S0}, %	$\Delta i_p^{(3)}$, %
		I_{S0}, kA	$i_p^{(3)}$, kA	I_{S0}, kA	$i_p^{(3)}$, kA		
1	400	9,590	27,100	9,585	27,084	0,052	0,059
6	33	24,190	66,200	24,059	65,565	0,542	0,959
7	33	24,300	66,380	24,175	65,829	0,514	0,830
10	0,4	38,140	93,610	37,642	91,949	1,306	1,774
13	0,4	41,180	101,120	40,538	99,100	1,559	1,998
36	0,4	47,150	114,720	45,451	110,507	3,603	3,672
16	6,6	21,430	59,450	21,288	59,027	0,663	0,712
29	6,6	22,110	61,010	21,943	60,529	0,755	0,788
26	0,4	34,050	78,340	33,437	76,494	1,800	2,356
33	0,4	48,370	114,490	46,727	110,522	3,397	3,466

Table 6.4 – Influence of c-factors on the results of the phase-to-earth short-circuit current calculations according to the IEC 60909

Location of the fault (node's number)	Voltage level, kV	IEC 60909		IEC 60909 (c-factor = 1)		ΔI_{S0}, %	$\Delta i_p^{(1)}$, %
		I_{S0}, kA	$i_p^{(1)}$, kA	I_{S0}, kA	$i_p^{(1)}$, kA		
1	400	9,570	27,030	9,560	27,020	0,104	0,037
6	33	24,830	67,860	24,600	67,040	0,926	1,208
7	33	24,910	68,020	24,680	67,210	0,923	1,191
10	0,4	30,510	74,880	29,95	73,15	1,835	2,310
13	0,4	31,750	77,970	31,12	76,08	1,984	2,424
36	0,4	40,510	98,570	39,12	95,12	3,431	3,500
16	6,6	22,140	61,410	22,02	61,05	0,542	0,586
29	6,6	22,620	62,410	22,48	62,01	0,619	0,641
26	0,4	26,280	60,460	25,69	58,77	2,245	2,795
33	0,4	38,940	92,190	37,69	89,15	3,210	3,298

It can be seen that in some cases, the c-factor gives the difference in results up to 3,6 %. The highest difference is observed at the 0,4 kV busbars because the biggest part of the short-circuit current goes through three step-down transformers in a row, which complex impedances are lowered by using the c-factor.

The second part of the difference between results calculated according to the IEC 60909 and GOST is a difference in the models of the power system elements. It is seen in the calculation of generator's and transformer's parameters that there are correction coefficients, which also decrease the complex impedance of the whole network and therefore increase the short-circuit current.

The third part of the difference between results calculated according to the IEC 60909 and GOST is inaccuracy in calculations. As lots of calculation according to the GOST were performed by hand, it is expected, that results have some inaccuracy. The more calculations were made, the higher inaccuracy could be – this statement can be proved by values in tables 6.1 and 6.2 where the difference in peak currents is higher than one in symmetrical short-circuit currents (calculation of the peak current is based on values of the symmetrical short-circuit currents).

6.3 Choice of the standard

GOST and IEC 60909 give slightly different results, usually, results according to the IEC 60909 are higher, i.e. more pessimistic. This fact influences the choice of the electrical apparatuses and equipment rating and leads to increase in the cost of the whole installation in comparison with the cost based on GOST's results. From the other point of view, using the GOST instead of IEC, we understate the safety margin of the electrical apparatuses and equipment rating, what means lower cost but also higher risk of damage or failure during the period of operation.

It's not correct to say that one standard is better and preferable than the other one, both of them have their benefits and drawbacks. Usage of the particular standard mainly depends on the customer's requirements and the location of the network.

Conclusion

During work on this diploma deep analysis of GOST R 52735-2007 and GOST 28249-93 standards was performed. These standards are relevant in the Russian Federation and regulate the short-circuit current calculations in the networks with rated voltage above and below 1 kV respectively.

The following main statements can be derived from the conducted research:

1) Investigation of GOST R 52735-2007 and GOST 28249-93 standards allowed to find and describe the universal and simple approach of calculation of short-circuit currents in the networks with the rated voltage of any levels. Chapters from 1 to 5 describe this approach in a step-by-step way;

2) Formulation of the theoretical part and use this theory in the practical part allows to clearly understand the whole process of the short-circuit current calculation according to the GOST standards;

3) Calculation of short-circuit currents in the industrial network using specialized software – RastrKZ allowed to obtain and evaluate results in a more proficient way and compare them with ones calculated according to IEC 60909-0 standard obtained using DigSilent software;

4) Evaluation and comparison of results obtained using both standards mentioned above allow to find difference in approaches of calculation of the short-circuit currents incorporated in them and make some conclusions about the area of use of these standards.

During work on this thesis, many skills which correspond to an engineer were obtained: understanding of basic and more advanced problems related to calculation of the short-circuit currents, ability to be focused on a formulated problem, correct evaluation of results of the performed work, ability to work with Russian and International standards and getting from there important and necessary information, knowledge in a basic calculation in RastrKZ and DigSilent software products.

References

1. *GOST R 52735-2007: Short-circuits in electrical installations. Calculation methods in alternating current electrical installations with voltage above 1 kV*, 2008.

2. *GOST 28249-93: Short-circuits in electrical installations. Calculation methods in alternating current electrical installations with voltage below 1 kV*, 1994.

3. *RD 153-34.0-20.257-98: Leading directions for short-circuit current calculation and choosing electrical equipment*, 1998.

4. *Leading directions for relay protection:* Short *circuit current calculations for relay protection and system automatics in power network 110 – 750 kV*, Energiya, Moscow, 1979.

5. International Electrotechnical Commission. *IEC 60909-0: Short-circuit current calculation in three-phase a.c. systems – Part 0: Calculation of currents*. Geneva: IEC, 2001.

6. Neuimin V.; Aleksandrov A. *RastrKZ software user's manual* [online]. 3rd edition. [viewed date: 1 September 2020]. Available from: < https://www.rastrwin.ru/download/Files/HELP_RastrKZ31.pdf >